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Gait Initiation Mechanics in Concussed Varsity Athletes

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Glossary of Terms and Abbreviations

Term	Definition
A/P	**Anterior/Posterior:** A directional term used to describe forwards and backwards movement in relation to the body
APA	**Anticipatory Postural Adjustment:** The activation of postural stability muscles needed in planned movement prior to voluntary activation
ATP	**Adenosine Triphosphate:** Cellular molecule used for transfer of chemical energy needed for metabolism
BESS	**Balance Error Scoring System:** Clinical tested developed for simple postural stability evaluations after a suspected concussion
BOS	**Base of Support:** Area of surface in contact with and between the feet.
Change-in-Support	**Change-in-Support:** A compensatory mechanism whereby a perturbation is countered by altering the base of support
CNS	**Central Nervous System:** Part of the nervous system that includes the brain and spinal cord
COM	**Centre of Mass:** Point in body where the sum of divided parts is equal to zero
CONC	**Concussed:** Short form used to represent concussed group
CONT	**Control:** Short form used to represent the control group
COP	**Centre of Pressure:** Summation point of all of the ground reaction forces into one vector
CoV	**Coefficient of Variability:** A statistical calculation used to normalize the dispersion of a probability distribution

CT	**X-ray Computed Tomography:** Computerized x-ray images of the brain that divides the brain into slices for viewing
EMG	**Electromyography:** A technique used to record the electrical activity within muscles
End Phase	**End Phase:** Final phase of gait initiation defined as the time between toe off of the swing limb to heel contact of the swing limb
Fixed-Support	**Fixed-Support:** A compensatory mechanism for a perturbation where the base of support does not change
Forceplate	**Forceplate:** A measuring instrument used to calculate the ground reaction forces generated by the body in contact with the ground
Gait Initiation	**Gait Initiation:** A self-generated perturbation where the body transitions from static stance to steady stance locomotion
GRF	**Ground Reaction Forces:** The forces exerted by an object in contact with the ground
ImPACT	**Immediate Post-Concussion Assessment and Cognitive Testing:** A computerized neurocognive assessment tool
Loading Phase	**Loading Phase:** Defined as the movement of the Centre of Pressure from static stance to the maximum posterior-lateral displacement
M/L	**Medial/Lateral:** A directional term used to describe side to side movement in relation to the body
MRI	**Magnetic Resonance Imaging:** Use of strong magnetic fields and waves to form images of the body
mTBI	**Mild Traumatic Brain Injury:** Medical term used to describe a concussion. Often used interchangeably

Optotrak	**Optotrak:** An active marker motion capture system designed primarily for gait analysis
Postural Control	**Postural Control:** The ability to control the body's position in space for the dual purposes of orientation and stability
Postural Stability	**Postural Stability:** The ability of a person to control the position and action of their body against the demands put upon it
PPC	**Posterior Parietal Cortex:** Key role in the production of planned movements
RMS	**Root Mean Squared:** A statistical measure of magnitude of a varying quantity
RTP	**Return to Play:** The amount of time needed from injury until medical clearance to play
SCAT3	**Sport Concussion Assessment Tool Version 3:** A screening tool using multiple test batteries for concussion evaluation
SIS	**Second Impact Syndrome:** At catastrophic incident where a second concussed is sustained prior to recovery from a previous injury
SMA	**Supplementary Motor Area:** Area of the brain responsible for the control of movement
Step Length	**Step Length:** Defined as the distance between two defined points of the foot in the A/P plane
Step Width	**Step Width:** Defined as the distance between two defined points of the foot in the M/L plane
Swing Time	**Swing Time:** A scalar measurement used to quantify the amount of time the swing limb is not in contact with the ground
Unloading Phase	**Unloading Phase:** Phase of gait initiation defined as the time from the maximum posterior-lateral displacement of the Center of Pressure until the toe off of the swing limb.

Abstract

Concussions are a common and potentially serious injury that affects athletes across multiple sports. More than ever concussions are now at the forefront of sport-related research.

Current research indicates that in a cohort of Canadian junior hockey players examined during the 2009-2010 season showed a rate of concussion at 36.5% of all athletic injuries (Echlin et al., 2010). This rate of concussion injury indicates that proper evaluations and examination tools are key to successful management of concussions. The objective of this study was to determine whether a functional task such as gait initiation is able to quantify stability difference following a concussion. It was hypothesized that the use of a functional task such as gait initiation will provide more sensitive and objective measures of balance control changes. The study used a total of 50 participants (22 males, 28 females) recruited from the Wilfrid Laurier University varsity men's and women's soccer, hockey, and basketball teams. Of the 50 participants, 10 represented athletes who had sustained a concussion (CONC) and 40 who had not received a concussion (CONT). Participants were required to stand on a force plate and initiate gait by taking a single step with their dominant foot towards a directional light (i.e., straight ahead or 30 degrees to either the left or right) as quickly as possible.

Results of the study indicated that CONC experienced significantly greater posterior COP displacement during the loading phase of gait initiation than the CONT. Excessive posterior displacement generated from the loading phase persisted throughout gait initiation and was recapture during the end phase. End phase step length and swing time was significantly increased in the CONC in comparison to the CONT. These results

suggest that the CONC group needed excessive posterior COP generation to overcome increased instability that is common during static stance prior to gait initiation (Powers, Kalmar, & Cinelli, 2014). Additionally, increases in step length and swing time are indicative of the central nervous system response needed to arrest COM momentum.

The findings from this study demonstrate that gait initiation is a sensitive and meaningful test in detecting individuals who were suspected to have experienced a concussion even after 72 hours post-concussion. Additionally, the study demonstrated that a gait initiation task is an objective measure of functional balance control that may be useful for assessing the recovery progression of an individual following a concussion. Gait initiation may be a good method to demonstrate balance impairments outside 72 hours post-concussion.

1 Background Information

1.1 Introduction

Concussions are a common, severe craniospinal injury that can induce life-long damage to the cognitive and physical well-being of an individual. A concussion (medically known as mild traumatic brain injury, mTBI) is defined as “a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces” (McCrory et al., 2013, p. 1). This process is outlined by the onset of short-term neurologic dysfunction whereby recovery time is variable in nature. This type of short-term injury represents a functional disturbance of the brain processes as opposed to a structural disturbance (McCrory et al., 2013). Recovery of neurological function follows a specified recovery pattern; however recovery can be long-term (McCrory et al., 2013). In the United State, an estimated 1.5 million individuals suffer from a mild traumatic brain injury (mTBI) each year (Thurman, Alverson, Dunn, Guerrero, & Sniezek, 1999). Of these 1.5 million, it is estimated that 80,000-90,000 experience long-term consequences (i.e. disability) associated with suffering an mTBI (Thurman et al., 1999). More recently, a study examining hockey players during the 2009-2010 season in a Canadian junior hockey league found that the rate of concussion was 36.5% (Echlin et al., 2010). Furthermore, this rate of concussion was far higher than the 3.1% previously reported in the National Hockey League (Echlin et al., 2010). In an effort to increase the understanding of concussions; researchers are examining the cognitive, physical, and symptomatic effects caused by an mTBI. Many clinical tests incorporate cognitive and symptomatic evaluations of mTBI in injured athletes. Some of the newer tests have expanded to include the physical signs of a concussion such as latency in reaction time and balance impairments. The latter is one of the more profound physical signs of mTBI and these problems can provide clinicians with a good estimate of mTBI severity and an objective measure to help structure their return-to-play decisions.

1.2 Disruption of CNS Function: Spectrum of Concussion Damage

From 1988 until 2004, mTBIs accounted for 9.8% of all injuries to National Collegiate Athletic Association (NCAA) women's lacrosse and 9.0% of NCAA men's hockey team's injuries (Agel, Dompier, Dick, & Marshall, 2007; Dick et al., 2007). These statistics indicate that mTBIs are a common problem across contact sports. However, mTBI is not limited to contact sports. For instance, NCAA soccer (8.6%) and basketball (3.9%) also recorded a high incidence of concussions (Dick et al., 2007). Within these four sports, concussions are the third most commonly experienced injury by athletes. Since mTBIs are a common occurrence across these sports, they need to be further researched to aid clinicians in return-to-play (RTP) decisions and to help prevent further injury.

1.2.1 *Mechanism of Injury*

Concussions are widespread disturbances that occur throughout the central nervous system (CNS). These disturbances create observed effects that are highly variable. This variability poses a significant challenge for clinicians to objectively evaluate an mTBI. Nonetheless, when a concussive insult occurs significant neurological impairments become evident. Mechanical forces acting on the skull cause the brain to accelerate and decelerate in a short time frame (Signoretti, Lazzarino, Tavazzi, & Vagnozzi, 2011). This movement is often accompanied by a severe impact with the skull causing severe and complex neurochemical and neurometabolical changes (Signoretti et al., 2011). This violent shaking of the brain triggers "ionic shifts, altered metabolism, impaired connectivity, and changes in neurotransmission (Giza & DiFiori, 2010; Giza & Hovda, 2001, p. 228)". Immediately following an injury, normal axonal cellular processes experience a cascade of neurophysiological damage. Normal cell mechanisms such as ion regulation are severely inhibited. This leads to a sudden and dramatic influx of calcium and efflux of potassium causing an imbalance in membrane potentials (Bentz & Purzycki, 2008). Therefore the sodium-potassium pumps must work excessively to reestablish membrane potentials internal and external to the cell. This places an increased energy demand within each cell of the brain. Humans experience a dramatic increase in glucose metabolism which is needed to produce Adenosine Triphosphate (ATP) to fuel the cell. After a concussive insult, this chemical process becomes immediately repressed and only exacerbates the problem of supply and demand (Giza & DiFiori, 2010). Additionally, there is a severe lack of cerebral blood flow making it difficult to deliver the needed ATP to each cell (Giza & DiFiori, 2010; Giza & Hovda, 2001). Giza & DiFiori (2010) term this as "cellular energy crisis" as the supply of energy cannot meet the excessive demand. This effect can be found in mild to severe traumatic brain injuries. Due to the compounding of factors, recovery from this type of injury can take weeks to months depending on severity (Bergsneider et al., 2001). Magnetic resonance imaging (MRI) studies have indicated that individuals who have experienced a concussion do not return to pre-injury levels until approximately 30 days post-injury through the measurement of the protein *N*acetylaspartate (NAA) (Vagnozzi et al., 2010). Therefore, recovery from a concussion does not simply resolve itself in a short time frame. Guskiewicz (2003) noted that 90% of athletes with a concussion were symptom free within 7 days post-injury with a mean resolution in 3 to 5 days injury. During this time the brain is highly susceptible to re-injury and can lead to SIS or post-concussion syndrome (Cantu, 1996).

Although it is important to understand the neurochemical changes following the injury, it is of equal importance to understand the mechanism of the insult to the brain. The direction, magnitude, and rotation of the insult to the head all contribute to the type of concussive damage received. Current research indicates that an mTBI can occur due to impact (i.e. when the head is directly subjected to external forces) or impulsive forces (i.e. when the head is indirectly subjected to external forces) (Sivak et al., 2005). The mechanisms that cause these head injuries are often linear, rotational, or angular forces (Poirier, 2003). Of these forces, rotational forces are thought to inflict the most amount of damage to the brain (Anderson, Heitger, & Macleod, 2006). Therefore the movement of the head following a rotational force could theoretically disperse the impact throughout most areas of the brain while linear forces cause a more localized type of injury. In cases where widespread brain damage does occur, the progression of a concussion is so highly variable and patient-dependent that prognosis is extremely difficult to quantify. Unfortunately, to date there are no definitive, quantitative measures that indicate the severity of injury. Not even the concussion grading scale can accurately predict the prognosis of an mTBI and because of this; the concussion grading is highly variable. It is because of this variability in diagnosis that clinicians are seeking out new alternative tests with more objective return-to-play measures that can help reduce the guess work in concussion management. Ultimately the development of new methods of assessing concussion symptoms can help clinicians reduce or eliminate further injury to the athlete (i.e. Second Impact Syndrome**).**

Second Impact Syndrome (SIS) is a condition where "an individual who receives an initial head injury receives a second head injury before the brain has recovered from the initial head injury (Cobb & Battin, 2004, p. 264) and can occur in the days and weeks after the initial concussion. Although this condition is rare, the seriousness of this syndrome should not be overlooked as it has lead to deaths in individuals of all ages. For instance there were 17 reported deaths related to SIS between 1992-1997 where the majority of these deaths occurred in high school athletes between the ages of 13-18 (Cantu, 1992; Cantu & Voy, 1995).

The defining characteristic of SIS is that it that head trauma occurs successively within a short period of time. There is no order to the events of SIS making outcomes patient-dependent. When an athlete suffers from two or more successive concussions in a short period this causes a compounding effect whereby damage is increased more than the sum of the concussions (Webbe & Barth, 2003). For example, suffering from two successive concussions does not equal a two fold increase in damage, but rather an exponential increase. Guskiewicz et al (2003) found that most repeat head injuries occur within ten days post-initial injury. This cumulative injury can be disastrous.

A detrimental aspect about SIS is that the symptoms may become long-term and increase in severity because the body's response to another head injury is highly variable, much like the initial mTBI. According to the American Academy of Neurology guidelines, individuals that received a concussion could return-to-play without difficulty within 15 minutes of initial injury. These guidelines rely on loss of consciousness as a key component for grading concussions and making return-to-play decisions (Cantu, 2001; Kelly et al., 1997; Silver et al., 2005). Based on these guidelines, if an individual does not suffer from loss of consciousness but still receives a head injury, he/she could be highly susceptible to SIS as they have returned to play before recovery from the initial injury has occurred. The SCAT3 and ImPACT tests attempt to eliminate the necessity for loss of consciousness to occur in order to receive an mTBI.

A less serious and more common post-concussion disorder that concussed athletes may experience is Post-Concussion Syndrome. Post-Concussion Syndrome is any "somatic, emotional, and cognitive symptoms that demonstrate short-term instability of the nervous system" (Cobb & Battin, 2004, p.263). Post-Concussion Syndrome is a precursor to SIS and symptoms may be present at five to ten days post-injury but can persist for weeks to months post-injury (Webbe & Barth, 2003). These symptoms mimic those of an initial concussion, which makes return-to-play decisions challenging especially with the pressure placed on the athletes from parents and coaches to return soon after injury.

The CNS is profoundly affected following an mTBI, resulting in many cognitive and physical manifestations of that damage. These manifestations are exceeding difficult to evaluate because they are highly variable across individuals. These variable manifestations include: 1) Cognitive, symptoms headaches, sleep problems, emotional problems, sadness, and nervousness; 2) A variety of sensory deficits such as: vision problems and sensitivity to light and noise; and 3) Many physical impairments such as:

Numbness/tingling, dizziness, vomiting and balance problems (Lovell et al., 2006). The focus of this study is to evaluate only one (i.e. balance) of the physical symptoms and the experimental conditions have been designed to objectively quantify this measure.

1.3 Current Clinical Tools for Evaluating Concussions

There are multiple tools currently in use that attempt to assess the damage sustained by a concussion. Two of the primary tests used by clinicians are: SCAT3 and ImPACT. The SCAT3, or the Sport Concussion Assessment Tool 3rd Edition is a clinical test developed by a group of international experts at the 4th International Consensus meeting on Concussion in Sport in 2013 (McCrory et al., 2013). Prior to this meeting it was established that a newer, more developed test was needed to evaluate concussions and so the researchers presented to its members the SCAT3. Developed by researchers, clinical guidelines for return to play have evolved over time.

Initially clinicians use two of the most commonly accepted evaluation guidelines: the Cantu and American Academy of Neurology to determine return-to-play for athletes. The Cantu guidelines are divided into three stages: Grade 1: no loss of consciousness and less than 30 minutes of amnesia; Grade 2: loss of consciousness for less than 1 minute and amnesia lasting for 30 minutes to 24 hours post injury; and Grade 3: loss of consciousness longer than 1 minute and amnesia that lasts more than 24 hours (Cantu, 2001).The American Academy of Neurology (AAN) has a similar but more extensive grading system: Grade 1: no loss of consciousness and confusion lasting 15 minutes or less; Grade 2: no loss of consciousness and confusions lasting 15 minutes or longer; Grade 3: 3a) brief loss of consciousness and 3b) prolonged loss of consciousness (Cantu, 2001; Silver et al., 2005). According to the AAN guidelines, an athlete may return to play if their signs and symptoms subside within 15 minutes of initial injury (Kelly, Rosenberg, & Stevens, 1997). However, both of these scales measure concussions with a loss of consciousness as a necessity to occur. Lovell and colleagues (1999) showed that loss of consciousness is a poor indicator of short-term neuropsychological recovery. Additionally, the researchers found that there is no significant relation between loss of consciousness and neuropsychological functions (Lovell et al., 1999). The requirement for loss of consciousness to occur during a concussion was modified at the 3rd International Consensus meeting on Concussion in Sport, indicating that loss of consciousness may or may not occur in a concussion (McCrory et al., 2009). Therefore there is no longer a functional application of the Cantu and AAN guidelines for evaluating return-to-play. These guidelines have been gradually phased out and the SCAT 3 and ImPACT tests have become a more reliable means to evaluate a concussion.

The SCAT3 testing protocol incorporates a simple, easy to use evaluation card that incorporates the cognitive, physical, and symptomatic symptoms of what is suspected to be a concussion. The SCAT3 conducts a symptom, cognitive, mechanism of injury and physical evaluation of an athlete is believed to have suffered from an mTBI. A collection of individual tests evaluate the condition of the individual (aged 10 and up) in under 30 minutes. The evaluation incorporates eight different tests that attempt to quantify when an athlete is ready to return-to-play. Some of these tests include: 1) the Glasgow coma scale, which is a short neurological test that evaluates the level of consciousness of a concussed individual (Teasdale & Jennett, 1974); 2) the standard assessment of concussion, which is a neurological test that evaluates orientation, acute memory deficits, concentration, and delayed recall; 3) the coordination examination, which evaluates upper limb coordination deficits; 4) symptom severity; and 5) the physical signs of a concussion (i.e. loss of consciousness, balance problems, etc.) (See Appendix C). Balance problems are assessed using the modified Balance Error Scoring System (BESS) and so for the purpose of this study it will be the tool used for comparative analysis.

The modified BESS is a simple, concise collection of sub-tests used to evaluate the postural stability of an individual who is suspected to have suffered a concussion. These sub-tests consists of individuals standing with hands on the hips in one of three positions: double leg stance (Figure 1a), single leg stance (Figure 1b), and tandem stance (Figure 1c).

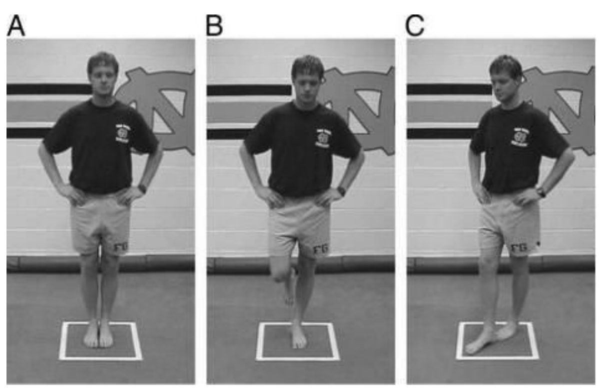

Figure 1: Modified BESS (Guskiewicz, 2001)

The individual is required to stand in these positions for 20 seconds with his or her eyes closed and the evaluator (doctor, athletic therapist, etc…) records the number of deviations from the desired stance position as errors. An error can include: Hands lifting off iliac crest, opening eyes, movement of the foot (step, stumble, and fall) just to name a few. This test is short and efficient, but it provides the evaluator with a skewed evaluation as the measured errors are only subjective in nature. This analysis is based on the judgments of the evaluator as he or she attempts to interpret the errors. While the BESS provides clinicians with tangible measures; the fact that balance is based on subjective data poses reliability problem for researchers. Finnoff and colleagues (2009) indicated that although certain sub-tests of the BESS are clinically reliable in evaluating postural stability, the total aggregate score outputted by the BESS is not clinically reliable. They further suggested that in order for a test to be considered clinically reliable, a coefficient above 0.75 is required and that the total BESS score had a reliability coefficient of 0.74, making it not very reliable. As well, clinical tests that incorporate the total BESS score rather than the sub-test scores lack intra-rater reliability. This indicated that the test as a whole does not output scores that are equivalent for all users of the tool. Therefore clinicians who base their return-to-play decisions on the total BESS score are not making the most accurate judgments about the player's recovery.

The second most common return-to-play evaluation tool for athletes following a concussion is the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT). ImPACT is a computerized neuropsychological test used for measuring attention and processing speeds in concussed athletes (Iverson, Lovell, & Collins, 2003). ImPACT testing provides clinicians with an alternative testing procedure that is designed to be a non-invasive, simple, and reliable evaluation. The reliability of the evaluation comes from the fact that it objectively quantifies an athlete's readiness to return-to-play. Although ImPACT does provide more objective measures of return-to-play, the test is expensive for the athlete, the scores need to be evaluated by a trained individual, and the test cannot be administered on-site which all impede the widespread use of the test. Additionally, ImPACT does not incorporate any type of balance assessment. Although not universal to all concussions, postural stability deficits exist in most TBIs and the inclusion of a postural stability assessment may to be beneficial.

The SCAT3 and ImPACT tests have greatly improve concussion evaluation for clinicians. However, return-to-play decisions still pose a significant challenge to clinicians because of the variability associated SCAT3 and ImPACT tests. A previous study by Iverson and colleagues (2004) showed that adolescent athletes who suffered from three or more concussions scored lower on baseline testing than age-matched controls according to ImPACT testing. Additionally, Iverson and colleagues (2004) found that athletes with multiple concussions exhibited more symptoms that are long-term in nature along with memory degradation not present in age-matched controls. These athletes were found to have cumulative effects from these short-term successive concussions according to ImPACT evaluations. Furthermore, they found that athletes with multiple concussions were 7.7 times more likely to suffer a catastrophic decrease in their memory performance compared to controls with no previous concussion history. This suggests that athletes should engage in testing over the long-term if he/she suffers from more than one concussion. The ImPACT test detected the cumulative effects of the concussion, but these individuals participated in baseline testing using ImPACT and were allowed to return-to-play after multiple concussions. This suggested that most clinical guidelines for return-to-play are too liberal and that a more sensitive measure of mTBI is needed to prevent SIS. This is concerning for certain sports (i.e. football, hockey, soccer) because the nature of these sports have a higher reported incidence of repeated head injury (Webbe & Barth, 2003).

Even the greatest concussion measurement tools cannot always reduce the likelihood of SIS. A factor that increased the likelihood of SIS is the reluctance of athletes to self-report head trauma to the athletic trainer, coach, or parents (Cobb & Battin, 2004). Athletic therapists may be able to determine when an athlete has sustained a concussion based on behaviors following a hit, but often times the subtle contact go unnoticed and in these cases the therapists rely on self-report. However, reluctance to report head injuries is due to fear of being removed from the game at a potentially crucial time.

1.4 Challenge of Maintaining Static Stability during Quiet Upright Stance

In healthy, young adults the integration of sensory, neurological, and musculoskeletal systems is required in order to maintain stability (Kuo, 2005). Successful postural control requires efficient functioning of these three systems in order for humans to remain stable in both static and dynamic states. If any of these systems are impaired or compromised, an individual's balance control has been shown to be severely affected (Guskeiwicz et al., 1997). Athletes who suffer from a mTBI exhibited impairments in one or all of the above mentioned systems leading to postural instability (Wade et al., 1997). Since damage to the brain following an mTBI is widespread and many different areas of the brain assist in controlling balance, the damage caused by an mTBI make it difficult to evaluate an mTBI (Hardman & Manoukian, 2002).

Previous research has shown that impairments in the balance control system decrease the ability to successfully perform everyday tasks such as standing and walking (Wade et al., 1997). Standing and walking place high demands on the balance control system thus when a pathology interferes with this system, stability is challenged. Postural instability is a common symptom associated with mTBI, which was frequently observed and studied in previous studies examining concussions in athletes (Basford et al., 2003; Geurts, Knoop, & Limbeek, 1999; Guskiewicz, Ross, & Marshall, 2001; Guskiewicz, 2001). The objectives of the previous studies were to determine the feasibility of using static balance control capabilities as a method assessing concussions. The results collectively showed that balance control is inhibited by mTBI during static balance situations. These objective measures of concussion progression can provide clinicians with an additional piece of information to base for their return-to-play decisions. Although these results were informative and important to understanding the effects and progress of an mTBI, the balance measures were performed only in a static, standing position. These studies lacked knowledge about postural control during dynamic (i.e. walking or stepping) stability. Since individuals do not stand in one location for extended periods of time and most feel unstable during locomotion, it is important to assess balance control in a dynamic situation. This is important because postural control impairments have been shown to be a more readily accessible measure of mTBI while preventing hasty return-to-play decisions (Guskiewicz, Perrin, & Gansneder, 1996). In order to understand postural control, a more thorough understanding of upright quiet stance is warranted.

Humans complete many tasks in an upright position, which significantly challenges our balance control system (Winter, 1995). Quiet upright stance (i.e. static balance or postural control) requires restricting the vertical projection of the body's centre of mass (COM) movements within a narrow base of support (BOS) as outlined by the lateral boarders of the feet (Gatev, Thomas, Kepple, & Hallett, 1999; Winter, 1995).

Humans, compared to other animals, have to maintain the COM within the BOS using only two feet (bipedal) as opposed to spreading this mass out over four feet (quadruped). Therefore, the COM is much more difficult to control during bipedal stance (Winter, 1995). In situations when the vertical projection of the COM falls outside of the BOS, a compensatory step is needed to prevent falling. However, to prevent a taking a step an individual must arrest the COM from moving outside the BOS by generating the necessary ground reaction forces (GRF) to oppose the COM's inertia. This GRF generation is compiled to an average distribution along or between one's feet called the centre of pressure (COP). The COP is constantly required to corral the COM and prevent falling. Therefore, this COM-COP relationship is shown to be intrinsically important for maintaining stability.

Stability is maintained through the generation of these opposition forces. In order to do so, the premotor cortex is thought to develop a sequence of actions used eliminate the effects of a perturbation and prevent falling (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Halsband, Ito, Tanji, & Freund, 1993). When an individual is in quiet stance, both COM and COP are localized between his or her feet. However, there are still noticeable movements of the COP and COM during quiet stance. The large mass above the naval being contained over a small BOS created by the feet is the primary cause of this inherent difficulty. Moreover this small BOS is the primary cause of instability and thus the cerebral cortex has to compensate through enacting muscle synergies generating proper force generation. In order the maintain stability, the cerebral cortex enacts muscle synergies through motor programs developed within the motor cortex and supplementary motor area that control muscle activation and control of stability (Brunt, Liu, Trimble, Bauer, & Short, 1999; Fiolkowski, Brunt, Bishop, & Woo, 2002a). Brunt and colleges (1999) further suggested that gait initiation and taking a voluntary forward step is controlled by the same motor program. This motor program may be stereotypical in nature but is thought to be modulated by the cerebral cortex through sensory input (Koski et al., 2002). As with all movements there are significant degrees of freedom problems that must be solved due to the number of joints (Bernstein, 1967). Bernstein (1967) suggested that goal-directed movement can be defined as the restriction of degree of freedom to achieve different coordinated movements. In other words, there are an infinite number of movement possibilities that are limited by the type of movement needed. Therefore the premotor cortex has limited selections for movement based on the joint and the musculature controlling the joint around the area (Bernstein, 1967).

Multiple theories exist as to the nature of this COM-COP relationship and how it is managed. Winter and colleagues (1998) hypothesized that a muscle stiffness model may be employed. This model states that force movements are involuntarily created about a joint that will oppose the inertia of the COM. The properties of inertia indicate that this mass will continue act in a specified matter until a force of any nature acts upon the mass to change its inertial properties. Inertia of the COM must be controlled by creating this muscle stiffness to maintain but not change quiet, upright stance. Ground reaction forces are required to generate movement that overcomes the muscle stiffness in order to corral the COM or if the properties of muscle stiffness cannot oppose the forces acting on the object (i.e. gravitational forces). If the body maintains upright stance following this model, then only during COM movements that surmounts these resting forces is the supplementary motor area required to engage in excessive compensatory measures through force generation.

Damage caused by a mTBI interferes with the ability of the CNS to analyze the situation and elicit compensatory measures during quiet stance (Wade et al., 1997). Following an mTBI this compensatory response has been shown to be highly variable. This is indicatative of stability also becoming highly variable (Wade et al., 1997). Individuals with an mTBI, long-term delays occur in a variety of dynamic motor tasks such as standing and walking (Parker, Osternig, van Donkelaar, & Chou, 2007). Parker and colleagues (2007) further concluded that these tasks were complex in nature and required a high level of attention in order to be successfully completed. The complexity and level of attention needed to successfully complete these tasks proves to be complicated for the CNS. The coordination of sensory feedback, action section, and motor output can be challenged after an mTBI has occurred. As such cannot provide the high degree of control needed to maintain stability. Multiple areas of the CNS are affected profoundly by an mTBI; inhibiting the ability of the supplementary motor area to coordinate motor tasks. If these systems are not functioning properly, maintaining upright stance becomes exceedingly difficult as is the case following an mTBI.

The ability to perturb the balance control system is relatively effortless, however the ability to identify pathologies based on balance control is an area of growing research. Geurts and colleagues (1996) were one of the first researchers to use balance control as a technique to measure mTBI progression. In that study, the researchers were able to measure stability by calculating the RMS of the COP velocity in the A-P and M-L directions. They determined that COP velocity was more sensitive to changes in stability and provided a good measure for comparative analysis across repeated trials (Geurts et al., 1996). The authors analyzed static and dynamic stability in mTBI athletes by having the athletes stand on a force plate with their hands comfortably behind their backs. Participants performed 5 different conditions: 1) quiet standing with eyes opened; 2) quiet standing while performing an arithmetic task; 3) quiet standing while wearing a pair of dark goggles; 4) weight shifting using visual COP feedback; and 5) visual-feedback-controlled weight shifting while performing an arithmetic task. The authors found that the mTBI group, when compared with control participants, exhibited significantly lower balance control as indicated by a higher COP velocity during both the static and dynamic conditions (Figure 2).

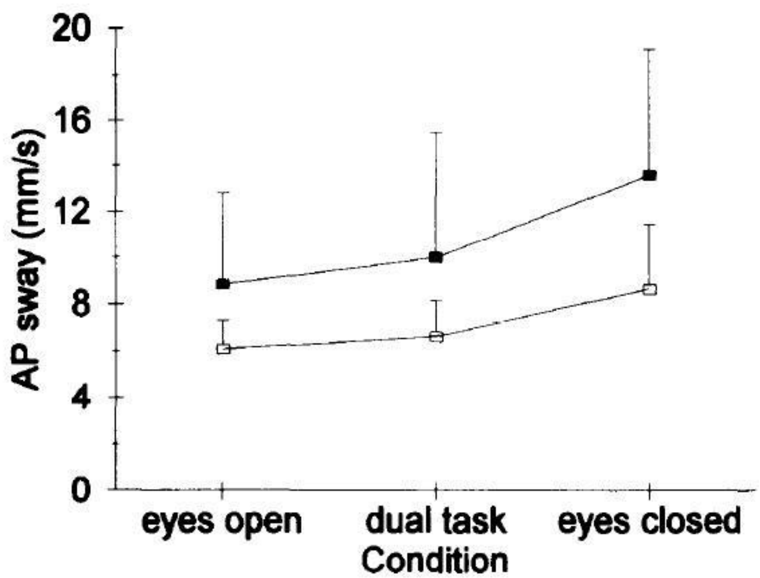

Figure 2a: Centre of Pressure Velocity in the Anterior/Posterior direction for concussed (dark squares) and non-concussed (white squares) individuals during three balance tasks (Geurts et al., 1996)

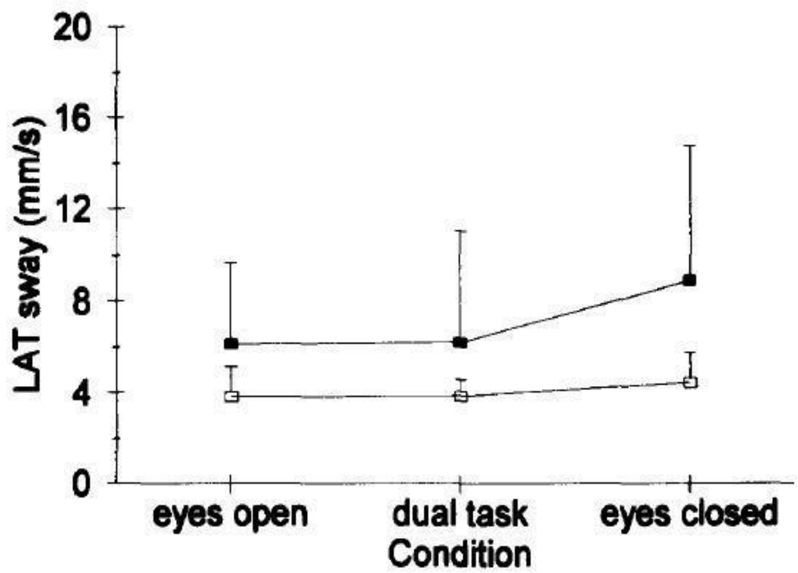

Figure 2b: Centre of Pressure Velocity in the Medial/Lateral direction for concussed (dark squares) and non-concussed (white squares) individuals during three balance tasks (Geurts et al., 1996)

Additionally, static stability tests showed that visual feedback is of great importance when maintaining stability especially in the mTBI group. This suggests that balance impairments could be due to sensory integration deficits in the mTBI group. Geurts and colleges (1996) concluded that postural instability is a long-term consequence after suffering from an mTBI. Since the greatest differences occurred during manipulation of the visual system, we have decided to partially duplicate this study and determine the feasibility of this analysis method.

As a follow-up to the study conducted by Geurts and colleagues (1996), Powers and colleagues (2014) analyzed static stability in varsity football players. The authors followed the athletes' recovery progress from initial injury to return to play to determine whether they had fully returned to baseline measures. The authors found that the concussed football players displayed greater A/P COP displacements during the acute phase as well as greater A/P COP velocity which persisted until return to play (Powers et al., 2014). This recent study supports the notion that postural instability occurs less in the M/L direction, but more so in the A/P plane of movement. Therefore assessing instability in the A/P plane of movement may be a feasible method of analyzing concussion recovery.

1.5 Sensory Integration and Sensory Dysfunction

The cause of instability may not necessarily be limited to dysfunction in the cerebral cortex of the brain. Successful sensory integration and processing of sensory information directly affects the ability of any healthy individual to remain stable and interpret their environment for proper control. The information provided by somatosensory, visual and vestibular systems are all used and interpreted in the visual and somatosensory cortex to maintain stability. The interactions with the environment through the 3 sensory systems relay that information to the cerebral cortex for processing. In the case of a concussion one or more of the sensory systems may be compromised. However, rather than experiencing a sensory system deficit following a concussion, individuals would more likely experience an issue with sensory integration.

The visual system provides information about the environment in a feed forward manner. During gait initiation, the visual system provides meaningful information about the environment and what is occurring at the time of initiation external to the body. However, the behavior of the COM during force generation as represented by the COP is equally dependent on feedback from both the somatosensory and vestibular systems. The visual system has been shown to be important in the development of successful gait (Patla, 1998; Winter, 1995). However, the primary focus of the current study was gait initiation and visual information was not recorded from the environment. Vision was not up-regulated as the success of gait initiation is more dependent on the other two sensory systems.

The somatosensory system represents a direct interaction through contact of the body with the environment relaying information in a feedback manner. The ability to detect touch, temperature, proprioception, and nociception provides extensive detail about an environment. It has been previously established that gait initiation occurs through force generation (ground reaction forces) elicited through a muscular response (Winter, 1995). The somatosensory system provides detailed information used in the regulation and selection of motor outputs needed to initiate gait successfully. However, it is highly unlikely that a concussive insult would induce damage to the sensory receptors or the sensory nerves. A concussion is more likely to affect the integration of this system within the primary somatosensory area found in the parietal lobe of the cerebral cortex. A disruption in visual and somatosensory information has been shown to have a detrimental effect on postural stability following a concussion (Guskiewicz et al., 2001). This rational cannot be eliminated as it is likely a contributing factor to postural instability. Guskiewicz and colleagues (2001) perturbed the visual and somatosensory systems by varying the environmental conditions detectable to each system. The types of disability elicited are not indicative of CNS or integration dysfunction but rather external factors. Furthermore, the authors concluded that in the case of a concussion "postural stability deficits can be best explained by a sensory interaction problem that prevents concussed athletes from accurately using and exchanging sensory information from the visual, vestibular, and somatosensory systems" (Guskiewicz et al., 2001 p. 271).

The final sensory system used for feedback is the vestibular system. According to Guskiewicz and colleagues (2001) the vestibular system serves 2 primary purposes in the maintenance of balance: 1) to maintain the eyes fixation on a stationary target in the presence of head and body movement; and 2) to maintain balance in conjunction with additional information from visual and somatosensory inputs. A disruption in vestibular input or the processing of this input may produce adverse effects on stability. After a concussion is sustained and the system is compromised, the concussed individuals could exhibit significant balance impairments. However, concussion typically displays a more neurological manifestation of damage compared to sensory damage. It is reasonable to conclude that although there is a sensory component to the balance control the main cause of instability prior to gait initiation could be due to CNS dysfunction located in the premotor cortex, supplementary motor area and possibly including sensory integration. Additionally, the vestibular system is up regulated during the more dynamic phases of gait rather than initiation due to the feed forward manner of initiation so vestibular contributions appear to be relatively low (Guskiewicz et al., 2001). However, it is important to note dysfunction in one or more of the sensory systems does not necessarily mean complete disability in all three systems. Gatev and colleges (1999) indicated that retention of stability occurs through the redundancy of sensory systems. The reweighting of sensory system information is based on multiple factors. Depending on the type of movement different sensory systems are up-regulated as their contributions are more pertinent to that situation. When an individual is walking through an environment vision remains the dominant sensory system needed to regulate movement (Patla, 1997, 1998). It is important to up regulate vision as vision provides information about the environment in a feedforward manner. Using the same paradigm, an individual who is visually impaired must up regulate other sensory systems. If in a concussed population one or more of the sensory systems are damaged then the redundancy of systems could protect from decreases in stability.

The CNS uses sensory feedback to elicit the appropriate response to prevent a perturbation. The supplementary motor area can only enact an appropriate responses based on sensory feedback it receives from the visual, vestibular, and somatosensory systems (D'Hondt et al., 2011; Guskiewicz, 2001; Kuo, 2005; Takakusaki, Tomita, & Yano, 2008). The contributions of each sensory system and their integration within the CNS play a large role in the development of appropriate motor responses to environmental cues during gait initiation. Previous research has shown that the vestibular system provides invaluable information regarding COM and head movement in the A/P plane (Bent, Inglis, & McFadyen, 2002, 2004). Powers and colleges (2014) found that there were significant increases in RMS COP velocity in the A/P plane. The authors further suggest that these issues may be due to vestibular damage, most likely poor sensorimotor integration in the lateral vestibulospinal tract. These findings may be applicable to the current study as vestibular damage may be a root cause of the decreased stability in the A/P plane while somatosensory deficits could explain decreased stability in the M/L plane.

2 Gait Initiation as Self-Perturbation to Balance Control System

Human locomotion is a product of environmental changes and thus requires constant adaptation to successfully execute (Gibson, 1958). The inherent difficulties in adapting to the environment have been well documented (Maki & McIlroy, 1997; Winter, Mcfadyen, & Dickey, 1991). In static stance, the demands placed on the balance control system are small compared to those of dynamic stability. When an individual is in static stance, the ability to maintain stability is relatively simple. In dynamic stability however, the level of balance control required to maintain stability is a product of the constantly changing environment as well as a constantly changing BOS and COM. In moving the body from static upright stance to steady-state locomotion; the first action is to move one's COM outside of his/her BOS to force a compensatory step and this continues throughout the gait cycle (Breniere & Do, 1991; Juan et al., 1993). The COM remains outside of the BOS for the duration of the gait event.

Concussed individuals have been shown to have observable, long-term deficits in gait stability (Cantena et al., 2009; Parker et al., 2006). Specifically, individuals with a concussion experience deficits in specific gait characteristics such as decreased step length, stepping velocity, and an increased step width to compensate for decreased stability. In a study by Chou and colleagues (2004); concussed athletes were found to have an increased sway and sway velocity during gait up to 28 days post injury. In order to off-set these balance control deficits, concussed athletes exhibited a more conservative gait pattern (i.e. decreasing gait speed and step length to maintain stability) (Chou et al., 2004). Researchers also noted that medial/lateral COM velocity increased, indicating that individuals with mTBI had difficulty maintaining dynamic stability in the frontal plane.

Previous work assessing individuals with a concussion have focused on changes in gait strategies throughout the course of the gait cycle. Previous research has failed to assess the mechanical and neural changes that occur with a concussed population in the earliest stages of gait: gait initiation. Gait initiation is a self-generated perturbation to the balance control system that moves the COM outside of the BOS through lower limb force generation (Winter, 1995). Once gait is initiated the body falls into rhythmic, stereotypical movements needed to successfully locomote across surfaces. However, gait initiation is the key to starting these rhythmic actions and thus the largest predictor of successful locomotion (Mbourou, Lajoie, & Teasdale, 2003). Mbourou and colleagues (2003) measured gait initiation in elderly adults, some of whom exhibited similar gait and balance difficulties that are observed in those with a concussion. The authors found that elderly fallers exhibited a more conservative first step length and longer duration in the double support phase of the gait cycle compared to non-fallers. The variability in the length of the first step was also shown to be double that of elderly non-fallers. The authors concluded that this gait variability may be an important predictor of postural stability deficits. Gait characteristics of a concussed athlete have been shown to closely match those of the elderly fallers, indicating that a connection might exist between concussed athletes and gait initiation (Martini et al., 2011; Muir, Rietdyk, & Haddad, 2014; Parker, Osternig, van Donkelaar, & Chou, 2008). Individuals with a concussion and elderly fallers have been shown to exhibit conservative gait patterns in an effort to maintain stability when the balance control system is compromised.

Gait initiation is complex task that requires successful integration of sensory systems, motor control, and the musculoskeletal system. . However, sequencing correct muscle activity to initialize gait requires precise motor coordination. The supplementary motor area is involved in the activation and deactivation of the lower limb musculature in order to initiate, maintain, and terminate gait. In order to achieve steady state locomotion, multiple steps are needed as sequential timing is crucial to success (Elble, Moody, Leffler, & Sinha, 1994; Winter, 1995). Coordination challenges are evident in the musculoskeletal system such as when gait initiation requires the gastrocnemius and the soleus to decrease activation in order to let the COM move outside of the BOS (Winter, 1995). Once this has been accomplished, the tibialis anterior is engaged to pull the COM forward, requiring the body to perform a compensatory step. This action of the tibialis anterior combined with the plantar flexors of the stance leg increase activation to create significant force for a push-off. These muscular actions generate ground reaction forces that when averaged represent the COP. The COM and the COP are intrinsically related.

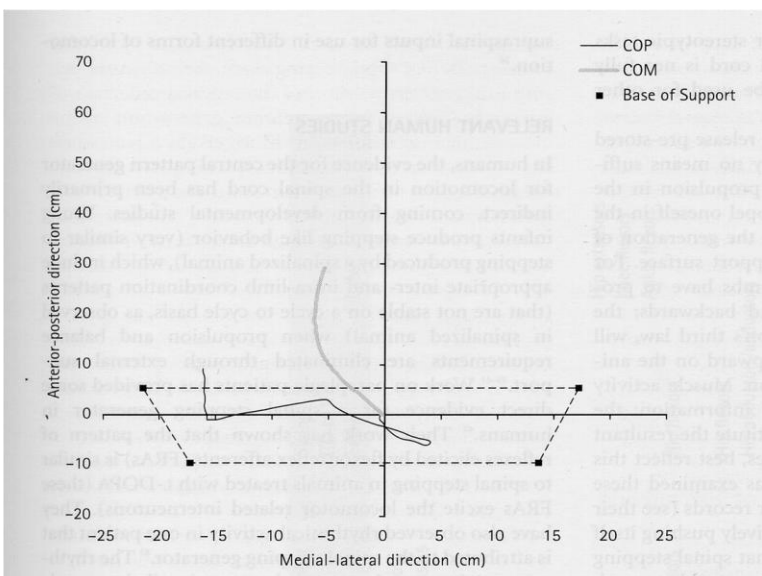

Figure 3: Typical movement of the COM and COP in relation to each other in a healthy young adult during gait initiation (Patla, 2004)

In order to manage this COM-COP relationship during gait initiation, the change in position of the COM must allow for the movement of one of the lower limbs. The movement of the COM onto and off of each limb, or loading/unloading is required for the successful implementation of gait initiation. Once it is determined that gait initiation is to occur, the COP moves from its resting position between the two feet posterio-laterally towards the swing limb, forcing the COM to move forward towards the medial boarder of the stance limb (i.e. loading). The COP then moves rapidly towards the lateral boarder of the stance limb to control the COM, forcing it to move anteriorly (i.e. unloading). Finally, the COM moves forward towards the swing limb so that it may accept the weight of the body, allowing the stance limb to move achieving steady state gait (Figure 4). The process of loading and unloading during gait initiation is a commonly occurring self-perturbation of the balance control system (Winter, 1995). Age matched controls exhibited substantial shifts in the medial/lateral COM as gait requires the loading and unloading of the COM on each leg. COM must be loaded on the stance leg during single support so that the swing leg may move to the next position to maintain the rhythmic gait pattern (Winter, 1995).

Prior to the initiation of gait, the supplementary motor area elicits a motor response that prepares the body for movement. The process, termed *anticipatory postural adjustments* (APA) is characterized by the deactivation of the soleus muscle combined with the activation of the tibilalis anterior, forcing the COP to move posteriorly before any movement occurs (Bent et al., 2002; Fiolkowski, Brunt, Bishop, & Woo, 2002b; Ito, 2003; Lepers & Brenière, 1995). An APA is a common, stereotypical movement activity that accompanies all transitional movements from a static to a dynamic state such as gait initiation (Ito, 2003). An APA directly impacts the ability of an individual to successfully initiate gait by providing the necessary movement preparation for the intended action. During the loading phase of gait initiation individuals in balance compromised populations have been shown to have difficulty creating stable APA's due to the complexity of gait initiation and the level of motor control needed (Brenière & Do, 1991; Elble et al., 1994; Winter, 1995).

Chou and colleagues (2003) noted that in individuals with an mTBI, these medial/lateral shifts of the COM occurred more frequently as individuals had inherent difficulties finding their stability point. This was due to the balance control system lacking the motor coordination needed to corral the COM, also observed in concussed athletes during quiet stance. Although these individuals were observed during obstacle crossing, they had noticeable changes in their gait parameters in order to maintain stability. Additionally, concussed athletes had a slower gait speed and a shorter stride length, which indicated a more conservative gait pattern. Finally, Chou and colleagues (2004) also found that concussed individuals exhibited greater M-L separation between their COM and their COP which indicated that they had greater difficulty stopping their sagittal momentum. This is concurrent with previous findings that the most observable sway in concussions was in the M-L plane. Martini and colleagues (2011) corroborated these findings by demonstrating that individuals with a history of concussions exhibited slower gait velocities than control individuals while spending more time in double-leg stance and less in single-leg stance. Although these studies examined difference among various gait parameters, the focus of the current study was to determine if gait initiation could provide a good representation of the balance control deficits experienced by an individual following a concussion.

When analyzing balance control in a concussed individual, static and dynamic stability must be considered. Previous studies examining static stance have shown that individuals with a concussion demonstrated acute postural instability lasting between 3 to 10 days post-injury (Cantu, 1996; McCrory et al., 2013). Static stability measures provide a good estimation of return-to-play for an individual, however they are functionally limited as it does not represent a situation in which balance is significantly challenged, as in a game situation. Dynamic stability control provides a more complete analysis of balance control especially in a concussed population. As well, it is more indicative of common action scenarios that an individual will routinely perform. Previous research of dynamic stability in concussed individuals has focused entirely on the gait cycle as a whole, lacking a sequential breakdown of each phase of the cycle. By separating the gait cycle into distinct stages for analysis, the effects of mTBI may be observed more closely in one or more of those stages. However, it may be difficult to conduct a gait assessment in concussed individuals because unless the system is challenged sufficiently, dynamic balance deficits following a concussion may not be observed. On the other hand, challenging one's dynamic stability too much following a concussion is not recommended. Therefore, previous work assessing dynamic stability following a concussion challenges individuals somewhere in between making it difficult to equate and compare findings from these studies.

The visual, somatosensory, and vestibular system all provide necessary feedback about the environment needed to engage in adaptive locomotion. Of these three systems, the vestibular system has been shown to have a profound effect on balance control during gait initiation (Bent et al., 2002). The vestibular system provides spatial orientation information about the environment, including movement and sense of balance. For their study of vestibular feedback, Bent and colleagues (2002) had individuals perform a forward stepping task with their eyes closed. Individuals stood on a force plate and were instructed to step forward onto another force plate to determine the accuracy of the step. Galvanic vestibular stimulation (GVS), which disrupts the functionality of the vestibular system by sending inaccurate data to the CNS was elicited on some trials. The authors found that GVS stimulation did not affect step initiation, but it produced changes to the medial/lateral location of the swing limb during more complex, dynamic phases of stepping. Changes in the COM-COP separation were noted during the toe off of stance limb and the heal contact of the swing limb (Figure 4).

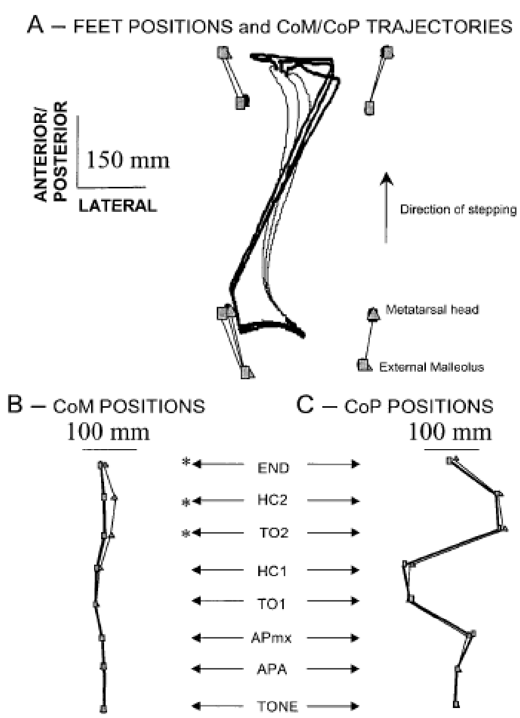

Figure 4: COM and COP profiles during gait initiation (Asterisks indicate significant COM-COP separation) (Bent et al., 2002)

These findings indicated that although vestibular information is not heavily up-regulated during step initiation, it is up-regulated during the latter stages of gait initiation. This study also indicated that the vestibular system provided essential feedback regarding sensation of balance during gait initiation. These balance control outcomes are similar to those shown by individuals affected with an mTBI, however the controlling neural correlate is less localized.

In humans, it has been shown that they are able to adapt to environmental changes during goal-directed locomotion (Winter et al., 1991). During unloading of the swing limb the COM and COP decouple to allow the COM and COP to act independently of each other. This allows improved adaptability to various internal and external perturbations. In the case of the current study, a neurological impairment such as a concussion could impact the control of the COM, COP or both at the same time. Through the decoupling of the COM and COP the behavior of the COP during initiation can change in such a way that it can either improve and stabilize gait initiation or not develop the necessary adaptations.

The uncoupling of the COM and COP is a strategy used to adapt to specific neurological impairments. One such neurological impairment occurs during gait initiation in individuals with Parkinson's disease. Gait initiation deficits in COM and COP movement have been well documents in individuals with Parkinson's disease (PD) (Elble, Cousins, Leffler, & Hughes, 1996; Halliday et al., 1998; Hass, Waddell, Fleming, Juncos, & Gregor, 2005a; Rosin, Topka, & Dichgans, 1997; Takakusaki et al., 2008). According to Takakusaki (2008) gait initiation deficits were characterized by hesitation of initiation, narrow steps, propulsions and postural stability deficits during walking. Individuals with Parkinson's disease often exhibit most if not all of these symptoms as the disease progresses. Since it is possible that the basal ganglia can be affected by a concussion injury it is also possible that concussed athletes may exhibit some or all of these gait initiation deficits. Elble (1996) suggested that individuals with Parkinson's who had greater COP displacement in the A/P and M/L plane took a longer step at the end phase. However in cases where COP amplitude was reduced, individuals with PD experienced significantly shorter steps while initiating gait (Elble et al., 1996). Although their cautious behavior is similar to the older adults in the study, individuals with PD exhibit different initiation patterns when compared to young adults (Halliday et al., 1998) (Figure 5).

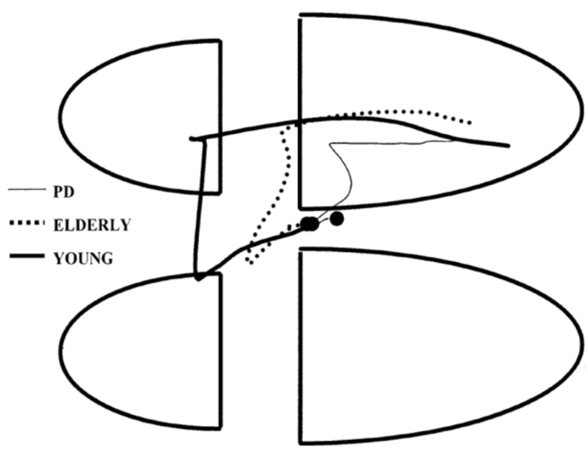

Figure 5: Time series COP patterns during gait initiation for young adults, elderly individuals, and Parkinson's disease individuals (Halliday et al., 1998)

By COP or COM independently, it can provide detailed information about the intended action. Previous research has shown that COP measures provided limited insight into those with postural control deficiencies (Rocchi, Chiari, Cappello, Gross, & Horak, 2004). Using COP measures separate from the COM to analyze postural stability has been shown to measure only the reactive response to the movement of the COM (Corriveau, Hébert, Raîche, Dubois, & Prince, 2004; Rocchi et al., 2004). The COM-COP relationship is needed for detailed movement analysis and this includes most important the relationship between COP & COM (Corriveau, Hébert, Prince, & Raîche, 2000, 2001; Corriveau et al., 2004; Winter, 1995). Previous research has also indicated that the COM-COP relationship is sensitive enough to detect dysfunction in postural stability (Corriveau et al., 2001, 2004).

2.1 Experimental Rational

Concussions continue to pose serious problems to athletes. The long-term effects of a concussion can be serious or even fatal (Lovell et al., 2004) In order to prevent lasting damage for athletes, researchers are making efforts to improve the management of athletes following a sports-related concussion. Pre-season baseline testing, acute diagnosis, and post-mortem examinations are recent developments within the last 10years in the sporting word. These measures have provided useful information that has led to improve concussion management and protect the athlete from returning to play prior to the resolution of symptoms and healing of the brain. However, the need to develop further testing is common among clinical practitioners and researchers alike. Gait initiation is a common and necessary event required for those who engage in rhythmic gait. Gait initiation provides clinicians and research with an observable task that can be objectively assessed in concussed individuals and monitor their recovery process. Gait initiation is defined by Elble (1994) as “ a purposeful, stereotyped sequence of postural shifts that propels the body over the stance leg and into forward motion" (p. 146). Further research by Halliday (1998) expanded upon this definition indicating that gait initiation is "a task that challenges the balance control system as it moves from stable static balance to continuously unstable gait" (p. 8). Using a gait initiation task for concussion analysis is a method of challenging the balance control system such that clinicians and researchers can monitor the recovery of baseline neurological functioning.

Neurologically, gait initiation is a descending drive initiation by the motor cortex and is unaffected by sensory feedback. This indicates that gait initiation is wholesome measurement of neurological deficits affecting balance control following a concussion. Gait initiation is not voluntarily modulated and therefore cannot deceive tests designed to monitor recovery when applied in concussion analysis making it highly objective. It is a simple task that is well-documented (Brenière & Do, 1991; Brunt et al., 1999; Elble et al., 1994; Halliday et al., 1998) and can be easily applied in a clinical setting. According to the Consensus statement on concussion in Sport: The 4th International Conference on Concussion in Sport the examination of balance (static or dynamic) remains an important part of concussion evaluation (McCrory et al., 2013). However, none of the current tests incorporate a dynamic balance evaluation. Maintaining dynamic stability is more demanding on the balance control system to maintain stability. By employing this simple yet challenging task a new method may be used in tandem with other test to objectively assess the presence of a concussion.

The objective of this study is to better quantify stability measures following a concussion by using a functional task in order to analyze the progression of concussion. Attempts were made to try and measure baseline values for athletes prior to the start of the season. However not all of the athletes had their baseline recorded. It is hypothesized that the use of a functional task such as gait initiation will provide more sensitive and objective measures of balance control changes. Specifically, multiple measures were used to compare healthy controls to the concussed group in the three phases of gait initiation. During the *Loading* phase it is hypothesized that the M/L COP displacement will increase significantly and that there will be no effect on A/P COP displacement. Additionally, the COP velocity will also increase significantly. During the *Unloading* phase it is hypothesized that the COP velocity will still remain elevated and the COM-COP displacement will decrease indicating greater control over balance while exhibiting a conservative gait initiation pattern. During the *End* phase, it is hypothesized that that step length and swing time will both increase due to the inherent instability of single support stance and the increased stability of double support stance with a larger base of support. The peak velocity of the swing limb will also increase so as to minimize time spent in single support. It is expected that changes to these measures will be synonymous with concussion progression in order to help objectively assess return-to-play criteria. We are predicting 10% of the active roster, or approximately 13 individuals that are injured players and meet the concussion criteria that are being examined.

3 Materials and Methodology

3.1 Participants and Testing Timeline

The current study included four varsity sports teams from Wilfrid Laurier University. The Control (CONT) group (N=39) represented athletes who had either never previously sustained a concussion or had not sustained one in the previous 6 months. The concussed (CONC) group (n=10) represented a different group of athletes from related varsity sports. The CONT group consisted of men's soccer (n=13), women's soccer (n=17), and women's basketball (n=9). The CONC group consisted of men's soccer (n=5), men's hockey (n=3), women's basketball (n=1)and women's soccer (n=1) (Table 1a). The CONT group had a mean age of 20.45 (±1.86) and an age range of 18-24. The CONC group had a mean age of 20.00 (± 2.01) and an age range of 18-24 (Table 1b).

Table 1a: Control and concussed participant demographics and history information

	Control	Concussed
Age (yrs)	20.45 (±1.86)	20.00 (± 2.01)
N	39	10
Men's Soccer	13	5
Men's Hockey	0	3
Women's Basketball	9	1
Women's Soccer	17	1
Days Post-Injury	N/A	9.63 (± 6.07)
Range Post-Concussion (Days)	N/A	3 to 19
Height (m)	1.73 (± 0.09)	1.79 (± 0.10)
Weight (kg)	67.36 (± 10.06)	75.00 (± 9.53)

Table 1b: Concussed participant demographics and history information

Participant	Weight (kg)	Height (m)	Testing Day Post-Injury	Concussion History
Participant 1	80.61	1.85	19	N/A
Participant 2	87.20	1.78	N/A	N/A
Participant 3	86.39	1.85	N/A	0
Participant 4	65.72	1.80	16	0
Participant 5	82.02	1.72	14	2
Participant 6	69.32	1.85	4	1
Participant 7	75.51	1.90	8	0
Participant 8	66.47	1.75	9	0
Participant 9	61.77	1.60	4	0
Mean	75.00	1.79	10.57	0.43
Standard Deviation (±)	9.53	0.09	5.88	0.79

* N/A represents missing data

Recruitment of participants occurred through the Athletic Therapy Clinic in the Department of Athletics and Recreation at Wilfrid Laurier University. The individuals from the CONC group were tested when they were symptomatic but able to complete the test. See Table 1 for further participant demographic information. Athletes from the varsity men's and women's basketball, and men's and women's soccer teams attempted to perform baseline testing at the start of the season to serve as a comparison if a mTBI occurred. However, not all baselines were obtained as athletes had the option of participation and some chose not to. Participants were included in the study if they were playing on one of the above mentioned teams or they received a concussion as determined by the athletic therapist. Three of the men's soccer players who had pre-season baseline data recorded also received a concussion. For statistical purposes these participants had their baseline data removed as the two groups were unrelated affecting statistical analysis. The concussed individuals were required to come into the lab for testing after they had received a concussion and were still within the symptomatic or the acute phase of injury.

Participants from this study were recruited through a WLU Golden Hawks Athletic Therapist who worked directly with the men’s and women’s soccer and women’s basketball teams. When a participant was suspected to have suffered a concussion, the athletic therapist performed a battery of tests (i.e., SCAT2) to determine whether or not the player was concussed. If participants received a concussion and had not previously been enrolled in the study they were asked to participate and complete the experiment. The concussed participants were allowed to enroll and complete the experiment if they received permission from the athletic therapist to do so. One of the major criteria used to determine if a concussed athlete was allowed to participate in the study was whether or not the individual could stand unassisted for 20 minutes without losing balance.

Athletes had no known neurological or behavioral impairments that inhibited their ability to perform gait, and were free of any physical limitations that affect their ability to conduct a forward step in multiple directions. Participants were excluded from this study if they had any cognitive impairments and physical limitations that severely affect maintaining postural stability. All participants were required to give informed consent (Appendix A) and fill out a medical information background (Appendix B) in order to gather information regarding injury history and demographic information. Participation in the study was strictly voluntary.

3.2 Experimental Setup

The entire experiment was conducted in the biomechanics teaching lab (AC 156). Prior to testing participants were required to fill out an informed consent. Participants were outfitted with Optotrack Infra-red light emitting diode (IRED) markers on the head with 1 rigid body consisting of 3 IREDs (M# 1-3). Three additional markers were placed on the trunk, two on the acromioclavicular joints (M# 4,5) of each shoulder and one on T10 (M #6). The trunk markers were used to estimate the location and movement of the COM. Furthermore, 2 markers were placed on the anterior ankle of each foot (M #7,9) as well as two on the 5^{th} metatarsals (M# 8,10) of each foot to measure foot kinematics of the dominant foot during the gait initiation task (Figure 8). Finally, marker 11 was placed on the anterior of the force plate initially used to detect when gait initiation occurred and synch the force plate with the Optotrak system, however this proved to be unreliable. One Optotrak position sensor was placed at the front of the room in order to collect data from a wide range of heights and body sizes. Kinematic data was sampled at 50 Hz.

Participants stood on a Bertec^{TM} Balance Plate forceplate with the medial aspects of both feet touching along the midline of the forceplate and with their arms at their sides. Participants were required to start in the same position for each trial. In order to start the forceplate and the Optotrak close to the same time, the Optotrak started prior to the forceplate and then the examiner signaled the assistant to start the forceplate. Kinetic data was sampled at 50Hz. A raised landing platform of similar height as the forceplate was constructed and place ahead of the participant such that the participant's dominant foot could land on the platform at the end of gait initiation. Prior to the beginning of the experiment the participant was required to take a few practice steps so that the landing platform was placed at a proper distance from the forceplate. This was done to ensure the participants' swing limb always landed completely on the landing board. The landing board was only used for landing of the swing limb and was raised to the exact height of the forceplate. Across the front of the room there were three red LED lights that were placed at approximately eye level for each participant. These LED lights determined the direction in which the participant was required to step in (Figure 4). The order in which each LED light illuminated was randomized.

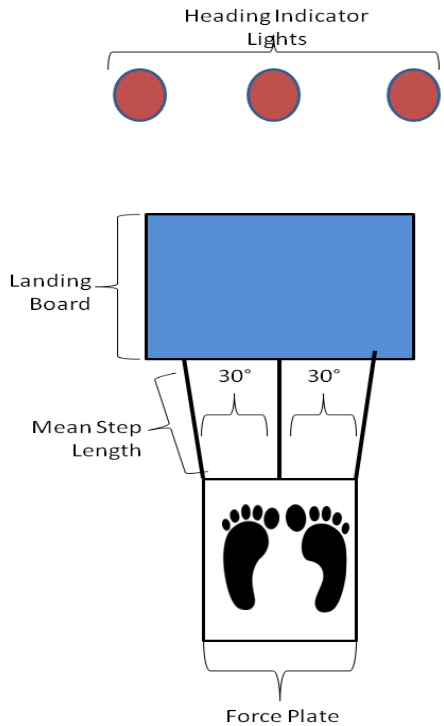

Figure 6: Experimental Set-Up (Birds' Eye View). Participants were required to stand with the medial aspects of their feet touching and facing toward the eye height LED lights and the Optotrak camera. Stepping occurred following the illumination of one of the LEDs with the dominant foot either straight ahead, 30° to the right, or 30°.

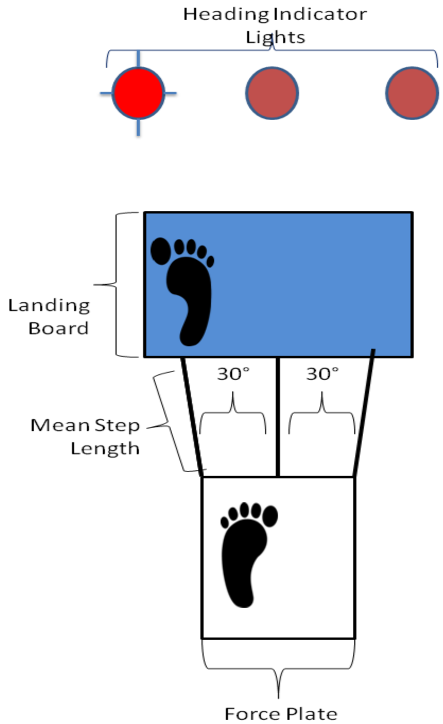

Figure 7: An example of a Stepping Pattern using the right foot following the illumination of the left LED. This stepping example occurred 30° to the left suggesting a step narrow approach

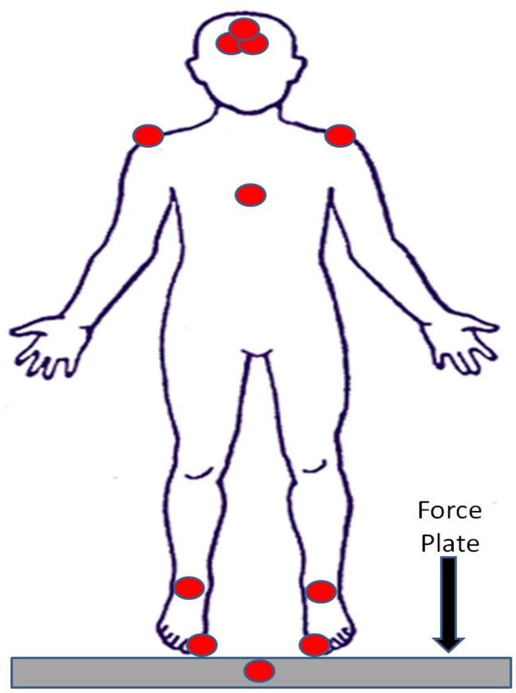

Figure 8: Optotrak 10 Marker Set-Up. The markers were located at head (3 rigid bodies), the left and right AC joint, the sternum, the left and right anterior ankle, and the left and right 5th metatarsal. Additionally, one marker was located on the anterior of the forceplate.

3.3 Procedure

Prior to the illumination of one of the LED lights, participants were required to stand quietly for the first few seconds of the test. Once the light at the front of the testing area illuminated, participants were required to step in the direction of the illuminated light with their dominant foot as quickly and safely as possible (Figure 6). Three stepping directions were chosen 30° to the right and left from center. Previous research indicates that the minimum degree change in direction needed to perturb the balance control system is 30° (Patla, Prentice, Robinson, & Neufeld, 1991). For the current study, it was determined that a 30° directional change should perturb the balance control system but not cause a severe destabilization. Participants were instructed to look at the LED lights and not where their feet were going to land on the landing platform. Once the participant stepped they were required to hold the position for a few seconds before returning to the starting position. Stepping directions were randomly assigned for each trial. Participants performed 18 randomized experimental trials (3 directional lights x 6 trials).

3.4 Data Analysis

Many of the measurements used during data analysis could be completed using only one measurement instrument. The forceplate and the Optotrak however had to be synched temporally in order for COM-COP analysis to occur. In order to accomplish this, the vertical position of the 5th metatarsal marker of the swing limb (denoted ‘Z’) and the vertical force component (also denoted ‘Z’) measured on the forceplate during gait initiation were used (Figure 8a) as time stamps to synch these two systems respectively (Figure 8b).

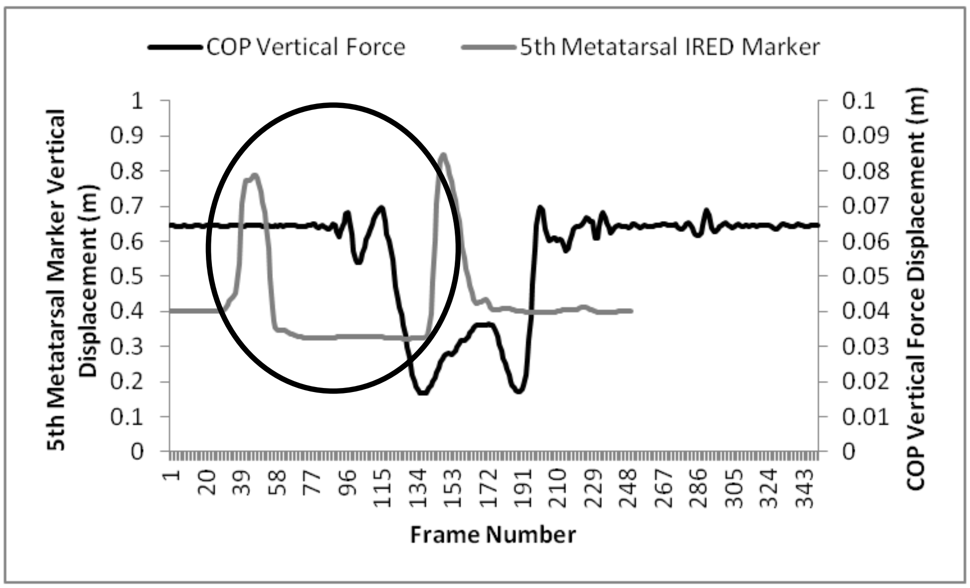

Figure 8a: Trial #5 from Men’s Soccer Player #8: Example of Optotrak (Red) and the Forceplate (Blue) prior to time synching of the data. Note the frame shift between the Optotrak and Forceplate as outlined by the black circle.

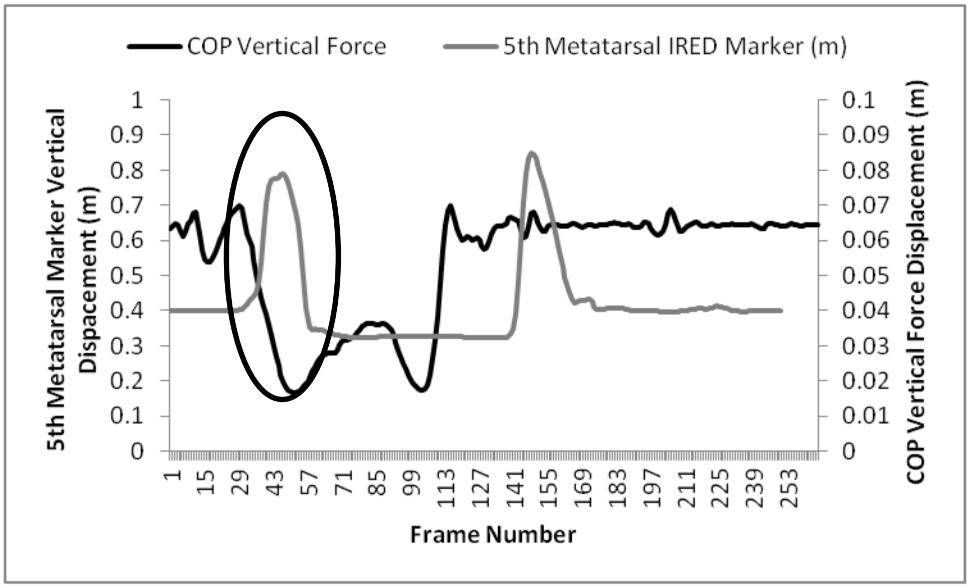

Figure 8b: Kinematic Output: Trial #5 from Men's Soccer Player #8: Example of Optotrak (Red) and the Forceplate (Blue) after time synching of the data. Note the frame shift (as outlined by the black circle) of the forceplate data to align with the Optotrak data, allowing for comparative analysis.

The Optotrak system was then synched to the forceplate by using the independent time stamps of the start of the vertical displacement of the participant's ankle of the swing limb and the COP force in vertical direction from the forceplate. The difference in time stamps between the systems for an event (i.e., toe off) was used to calculate and remove the bias between the systems and shift the Optotrak data to that of the forceplate.

Kinematic analysis was conducted by analyzing multiple variables output by the Optotrak Certus system. Centre of mass (COM) displacement and velocity in the A/P and M/L directions, step length, and step width and swing time were analyzed in each phase of gait initiation. The weighted COM calculation was based off of models previously outlined by Gard and colleagues (2004) and Winter (1995). However it was decided that the COM weighted calculation using only the torso markers would be employed using the following calculation: $COM = (Left\ Shoulder\ Marker * 0.25) + (\mathrm{T12} * 0.5) +$

$(\text{right shoulder mark} * 0.25)$. This calculation may not be representative of what is the COM was actually doings during the task. Using a multi-segmental model that incorporated all body segments may have been a more accurate calculation because the nature of the task was mostly lower limb movement. However, the 3-marker COM calculation was selected as it was assumed that any COM movement would be dominated by the torso and also we wanted to ensure that we minimize time spent during set-up of the participants. The COM displacement was used to calculate the COM velocity and for later calculations in the COM-COP relationship. COM velocity was calculated by taking the resultant COM location over the duration of the trial and dividing it by the total time of the trial.

Forceplate measures were used to collect kinetic data of ground reaction forces in relation to static stance and gait initiation. From the forceplate, the COP vector displacements were calculated for both the M/L and A/P directions. The calculation of both the COPs were included in the software and output to a file from the forceplate. COP displacement was normalized by subtracting the first data point from all of the subsequent data points This information is crucial to defining the phases of gait initiation (i.e., *Loading, Unloadin*g, and *End*) as outlined by Winter (1995).

3.4.1 Loading Phase

The *Loading* phase was defined as the time period between the stable static stance (quiet standing) and the maximum posterior-lateral shift of the COP towards the eventual swing limb. The *Loading* phase was broken down into 2 components: 1) the medial-lateral (M/L) displacement (Figure 9a); and 2) the anterior-posterior (A/P) displacement (Figure 9b) of the center of pressure (COP).

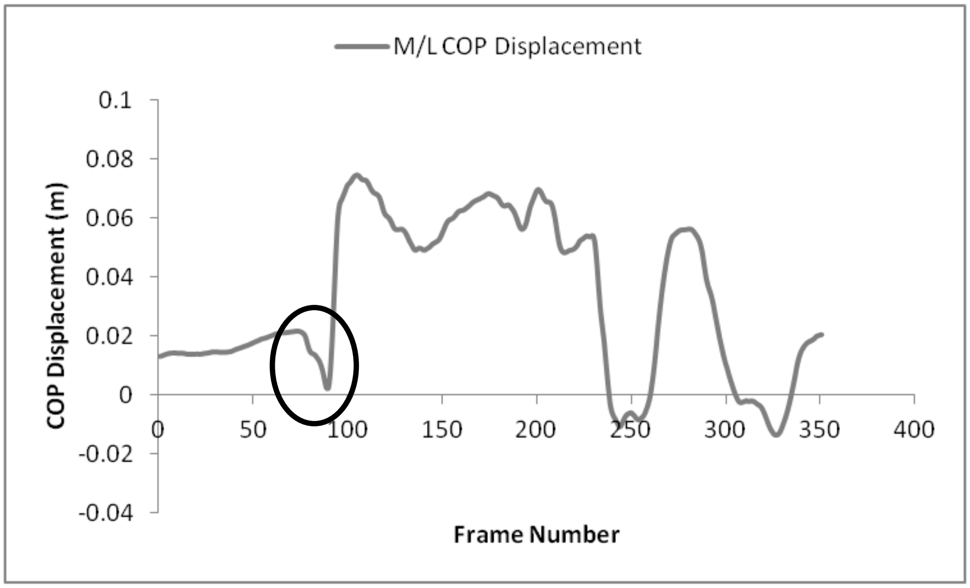

Figure 9a: Kinetic Data: Sample center of pressure displacement in the M/L plane. Positive displacement indicates a greater lateral shift. Note the loading phase denoted by the red circle.

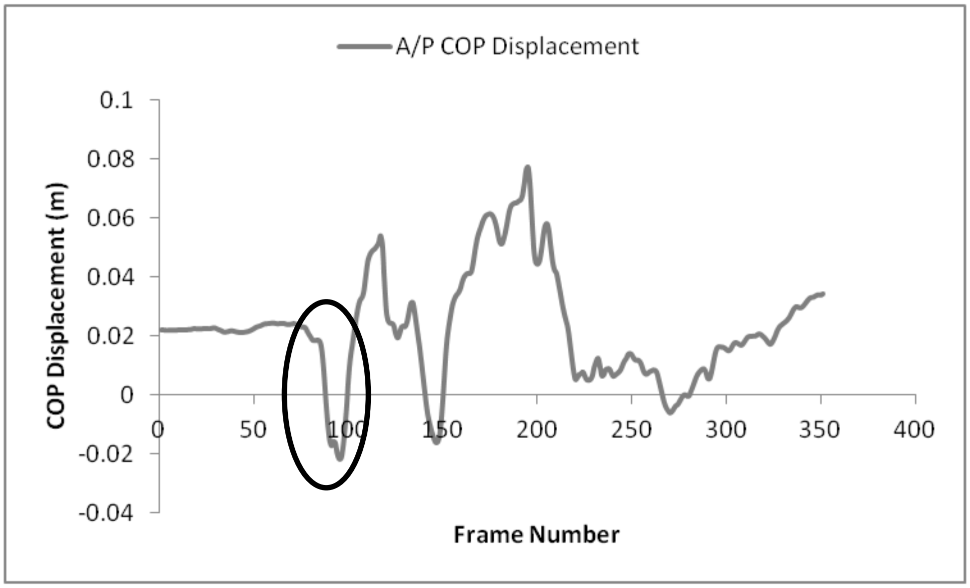

Figure 9b: Kinetic Data: Sample center of pressure displacement in the A/P plane. Positive displacement indicates a greater lateral shift. Note the loading phase denoted by the red circle.

3.4.2 Unloading Phase

The *Unloading* phase was defined as the end of loading (maximum M/L COP displacement) until toe off of the swing limb. The Unloading phase was broken down into 2 components: **1**) maximum COM-COP M/L displacement (inflection point 1) and **2**) minimum M/L COM-COP displacement (Inflection point 2) as a measurement of their stability margin (Figure 10). Inflection points were calculated using a displacement-time graph and were selected when the participant displayed a change in direction. This was calculated by taking the first derivative of the displacement-time graph to outline where the inflection points occurred. These points corresponded with the maximum displacement between the COM and the COP and the minimum displacement of the COM and COP occurring at toe-off.

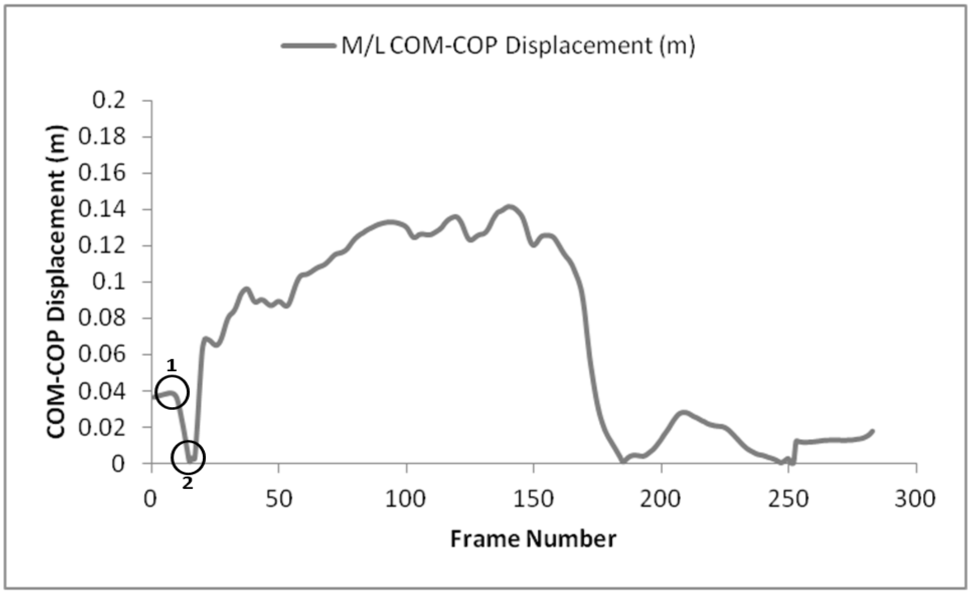

Figure 10: Kinetic Date: Sample Trial #11 from Men's Soccer #8: Measurement of the COM-COP displacement. 1) denotes the maximum M/L COM-COP displacement (represents 1st inflection point on a velocity time graph) 2) Denotes the minimum M/L COM-COP displacement (represents the 2nd inflection point on a velocity time graph)

3.4.3 End Phase

The *End* phase was defined the beginning of toe off of the swing limb until heal contact of the swing ling in the proper direction. This phase was calculated by using the same specific time points as the swing phase as they correspond directly with the temporal variable of the swing phase. Step length (m) was measured using the anterior ankle of the stance limb subtracted from the anterior ankle of the swing limb. The Y component of the anterior ankle marker was used as it represented movement in the A/P plane. For the stance limb an average of the anterior ankle placement was used. For the swing limb once the anterior ankle had stopped moving within 3 standard deviations an average was complete during static time (Figure 11). To remove the bias of differences in height or leg length, step length was normalized to each participant's height. . Movement of the anterior ankle was defined as anything outside of 3 standard deviations. Step width

(m) is also calculated by using the same method as the step length only in the M/L direction.

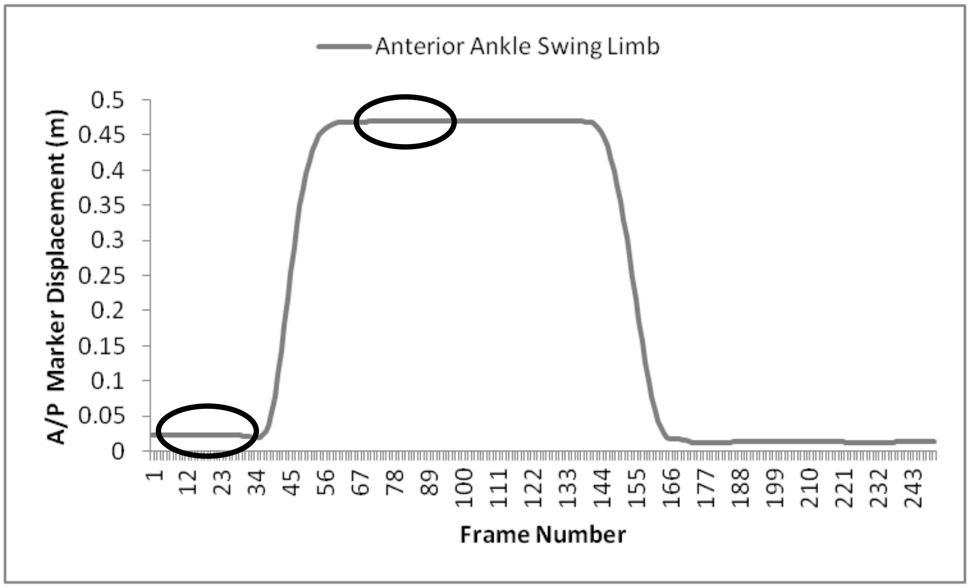

Figure 11: Kinematic Output: Sample Trial from Men's Soccer Player #8. The red circles denote when the average initial and final foot placement was calculated. Step length was calculated by subtracting the final foot placement to the initial foot placement. Forward movement is indicated by a positive displacement.

Additionally, swing time (s) was calculated using the anterior ankle marker. This was calculated simultaneously with step length analysis. It was determined that when the swing limb was static prior to and after swing that the start and end times for swing time would correspond to step length. However, as opposed to using an average like the one employed during a step length analysis, specific time points were selected on the basis of arrested movement prior to and after 3 standard deviations.

3.4.4 Statistical Analysis

For statistical analysis all dependent measures were compared using a mixed model analysis of variance (ANOVA) with 2 between levels (i.e. Group: Control and Concussed) and 3 levels (i.e. Stepping Direction: Wide, Straight, Narrow). Multiple dependant variables were analyzed. The M/L and A/P COP displacement was analyzed during the *Loading* phase. COM and COP range, COM velocity and COM-COP displacement were analyzed during the *Unloading* phase. Finally, during the *End* phase step length, step width, swing time, peak velocity and final foot placement variability were all analyzed. Baseline data was compared to concussed data. The two groups were not related so therefore this is not a repeated measures analysis. The main effects examined were heading and group. All post-hoc analyses were performed using the Bonferroni correction. Variability was analyzed by using a coefficient of variation calculation. Coefficient of variation was calculated using the formula: $CoV = \frac{SD}{M}$, where SD= Standard deviation and M= Mean. This was done so that the variability could be normalized across all populations and measures for equal comparison. Standard deviations were used on all figures to provide a graphic representation of the variability for each variable.

4 Results

4.1 *Loading Phase*

In order to quantify differences between the CONT and CONC group during the *Loading* phase, COP excursions were examined and broken down into A/P and M/L components. This was done in order to gain an understanding one's ability to effectively manipulate the COP to separate the COM and COP and allow for gait initiation to occur. Previous research has shown there to be a significant decrease in M/L COP displacement during the loading phase of older adults and individuals with Parkinson's disease (Halilday et al., 1998). This measure was indicative of decreases in postural control in the M/L direction. More recently Powers and colleagues (2014) indicated that athletes who received a concussion displayed significantly increased A/P COP displacement. This decrease in postural stability was thought to be due to changes in the output of the vestibular nuclei. It was postulated that there would a significant increase in both M/L COP displacement and A/P COP displacement in the CONC group during the loading phase.

<u>M/L COP Displacement</u>

Table 1 shows the M/L COP displacement means and coefficients of variation (CoV) separated by Stepping Direction and Group. Results of mean M/L COP displacement revealed that there was no significant main effect of Group (Control, M=0.027m; Concussed, M=0.026m) ($F_{(1,45)}$= 0.141, p=0.709) (Figure 1a).

Results of M/L COP displacement CoV displayed no significant effects of Group (Control, CoV=0.464; Concussed, CoV=0.515) ($F_{(1,45)}$=0.793, p=0.378, r=0.354). Results also indicated a trending interaction effect of Group by Stepping Direction $F_{(1.546, 69.552)}$=2.869, p=0.076) (Table 1). In the Step Wide condition, there was a significant increase in CoV in the concussed population (p=0.041).

Table 1: Overall mean and coefficient of variation (CoV) values of M/L COP Displacement (m) for the CONT and CONC groups across each Stepping Directions.

Stepping Direction	Control (Mean)	Concussed (Mean)	Control (CoV)	Concussed (CoV)
Step Narrow	0.035	0.037	0.421	0.363
Step Straight	0.037	0.027	0.402	0.388
Step Wide	0.019	0.015	0.570	0.796

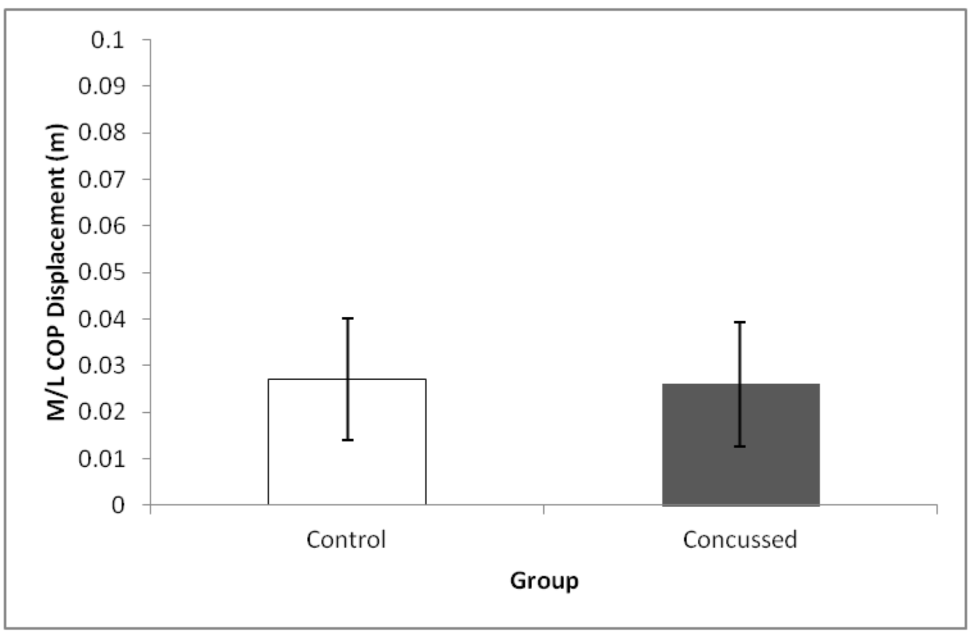

Figure 1a: Mean M/L COP Displacement collapsed across three stepping directions. There was no significant difference in M/L COP displacement between the CONT and CONC group. Additionally, there was no significant different in M/L COP displacement variability. This indicates that there is in inherent variability associated with the movement and that M/L stability can be effectively maintained.

A/P COP Displacement (m)

Table 2 shows the means and CoV of the CONT and CONC group separated by Stepping Direction and Group. The results of the mean A/P COP displacement revealed that there was a significant main effect of Group (Control, M=0.062m; Concussed, M=0.046m) where Concussed demonstrated significantly larger COP displacements (i.e. posteriorly) than Controls ($F_{(1,45)}$=4.869, p=0.032, r=0.354) (Figure 2a). There was no significant interaction effect of Group by Stepping Direction ($F_{(2,90)}$= 0.290, p=0.787) (Figure 2b).

The results of the CoV of the A/P COP displacements indicated that there was neither a significant effect of Group (Control, CoV=0.294; Concussed, CoV=0.345) ($F_{(1,45)}$ = 0.105, p= 0.748), nor an interaction effect ($F_{(2,90)}$ =1.105, p=0.787).

Table 2: Overall mean and coefficient of variation (CoV) values of A/P COP Displacement (m) for the CONT and CONC groups across each Stepping Directions.

Stepping Direction	Control (Mean)	Concussed (Mean)	Control (CoV)	Concussed (CoV)
Step Narrow	0.042	0.056	0.389	0.288
Step Straight	0.049	0.066	0.352	0.304
Step Wide	0.048	0.064	0.294	0.290

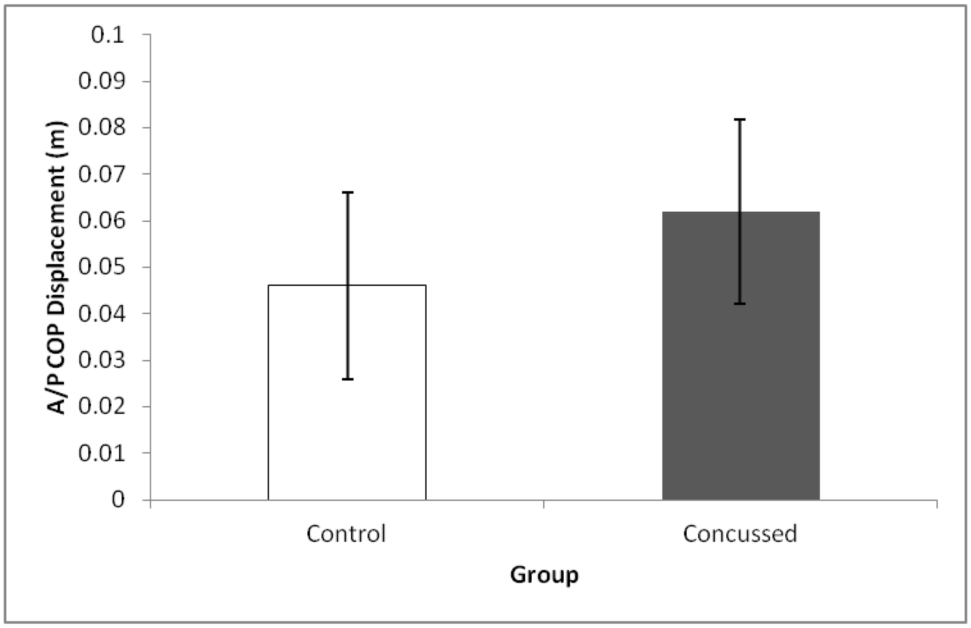

Figure 2a: Mean A/P COP Displacement collapsed across three Stepping Directions during the Loading phase. There was a significant difference between the CONT and the CONC groups. Mean A/P COP displacement was significant higher in the CONC compared to CONTindicating an potential increase in postural instability in the A/P plane Additionally, there were no significant differences in A/P COP displacement variability.

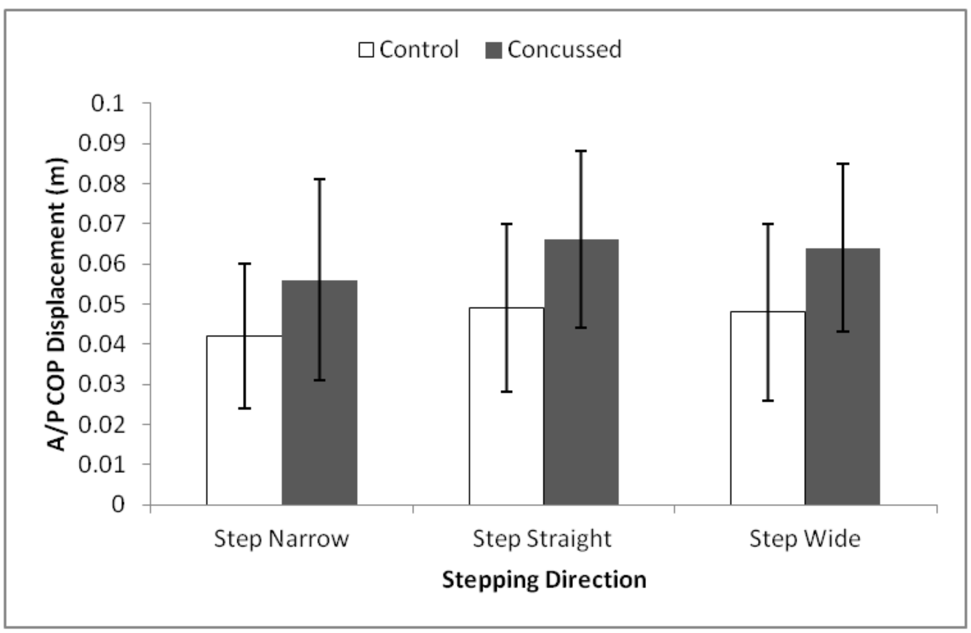

Figure 2b: When A/P COP displacement is separated across stepping directions it indicates that increases in A/P COP displacement is univeral across all three stepping directions and not localized to one or two directions.

4.2 *Unloading Phase*

During the *Unloading* phase of gait initiation there were two specific temporal events were selected to analyze the behavior of the COM and COP relationship: the minimum and the maximum M/L COM-COP displacement difference. The maximum M/L COM-COP displacement occurs at the end of loading and the start of unloading while the minimum COM-COP displacement difference occurs at some point just prior to toe off of the swing limb. Each event allows for the quantification of an individual's change in stability as the COM overcomes momentum by moving from a static state to a dynamic state. This measure was chosen over A/P analysis because the M/L COM-COP relationship is more indicative of instability that occurs during the unloading phase. Additionally, previous research has shown that the COM-COP relationship is a good measure of stability because it can demonstrate whether or not the COP was able to cause a larger separation from COM (Corriveau et al., 2001; Hass, Waddell, Fleming, Juncos, & Gregor, 2005b). It is postulated that there will be a significant decrease in COM-COP displacement in the CONC group, indicating a tightly controlled unloading phase and a conservative gait initiation strategy.

<u>Maximum Stability Margin (m)</u>

Table 3 displays the means and CoV of the CONT and CONC group separated by Stepping Direction by Group for the maximum COM-COP displacement difference (i.e. Stability Margin). The results of mean maximum difference revealed no significant main effect of Group (Control, M=0.043m; Concussed=0.043m) ($F_{(1,41)}$= 0.019, p=0.892, r=0.023) (Figure 3a). However, the results demonstrated a significant interaction effect of stepping direction by group during the step wide condition ($F_{(1.499, 61.445)} = 4.587$, $p=0.022$). Post hoc analysis revealed that there was a significant decrease in maximum M/L COM-COP difference across all headings except stepping wide (Figure 3b).

Results of CoV of the maximum COM-COP displacement difference revealed that there was neither a significant effect of Group (Control, CoV= 0.739; Concussed, CoV= 0.388) ($F_{(1,40)} =0.263$, $p=0.611$) nor an interaction effect ($F_{(1.010, 40.415)} = 0.317$, $p=0.579$).

Table 3: Overall mean and coefficient of variation (CoV) values of Maximum COM-COP Displacement (m) for the CONT and CONC groups across each Stepping Directions.

Stepping Direction	Control (Mean)	Concussed (Mean)	Control (CoV)	Concussed (CoV)
Step Narrow	0.046	0.037	0.362	0.351
Step Straight	0.037	0.036	0.840	0.485
Step Wide	0.046	0.057	1.005	0.329

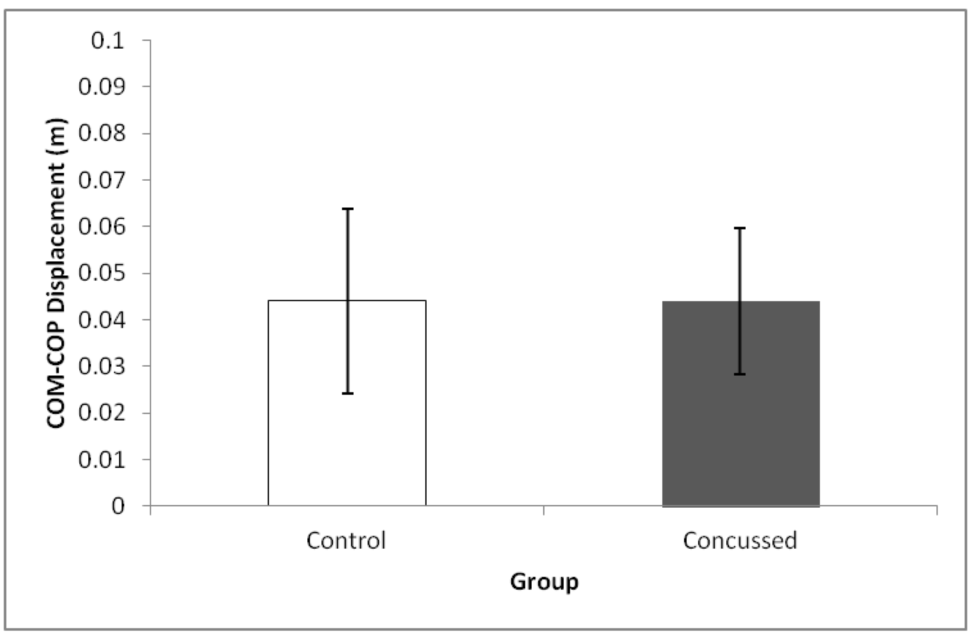

Figure 3a: Mean Maximum COM-COP Displacement collapsed across all Stepping Direction during *Unloading* between the CONT and CONC groups. This is indicative of a similar level of postural stability between the CONT and CONC that allows the COM

to behave similarly regardless of concussion. No significant differences noted between maximum COM-COP Displacement variability indicating that variability does not change post-injury.

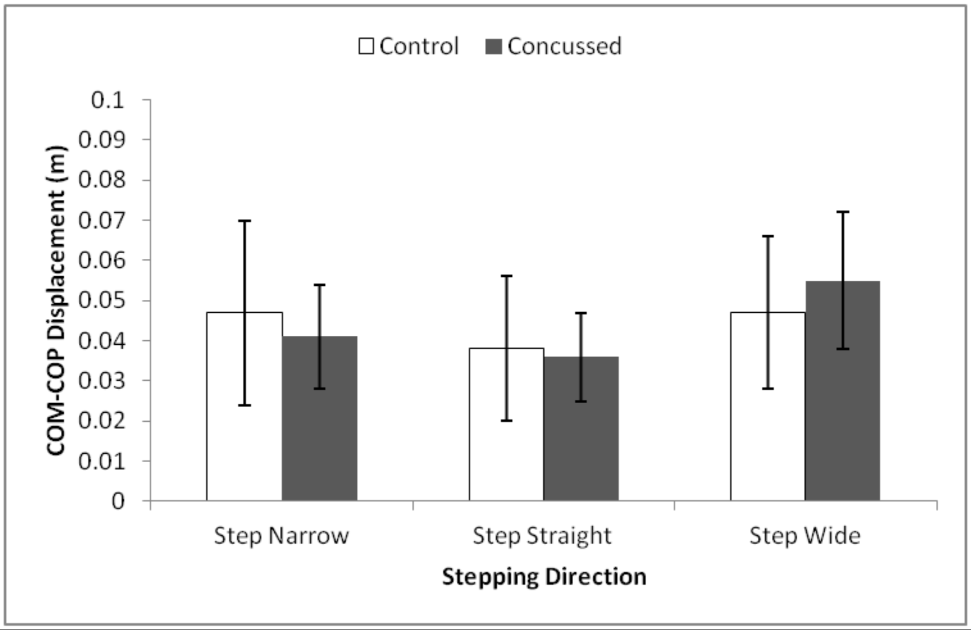

Figure 3b: Mean maximum COM-COP Displacement separated by Stepping Direction and Group including standard deviation. Noted significant interaction effect of stepping direction by group. Results indicate that COM-COP displacement increased in the step wide condition. No significant variability effects ($p<0.05$).

Minimum Stability Margin (m)

Table 4 shows the means and CoV of the CONT and CONC groups' minimum M/L COM-COP displacement separated by stepping direction and group. The results of the mean minimum COM-COP displacement difference revealed that there was a significant main effect of Group (Control, M=0.003m; Concussed, M=0.005m) whereby the Concussed group demonstrated a significantly greater difference than the Control group ($F_{(1,37)}$= 4.700, p=0.037, r=0.092) (Figure 4a). However, there were no significant interaction effect of the minimum Stability Margin difference ($F_{(1.399, 60.170)}$= 0.063, p= 0.879) (Figure 4b).

The results of the CoV of the minimum COM-COP displacement difference revealed that there was neither a significant Group effect ($F_{(1,41)}$=0.428, p=0.521) (Control, CoV=0.874; Concussed CoV=0.912) nor an interaction effect ($F_{1.897, 77.764)}$= 1.274, p=0.284).

Table 4: Overall mean and coefficient of variation (CoV) values for Minimum COM-COP Displacement(m) for the CONT and CONC groups across each Stepping Directions

Stepping Direction	Control (Mean)	Concussed (Mean)	Control (CoV)	Concussed (CoV)
Step Narrow	0.004	0.004	0.913	0.981
Step Straight	0.003	0.005	0.898	0.946
Step Wide	0.002	0.004	0.810	0.810

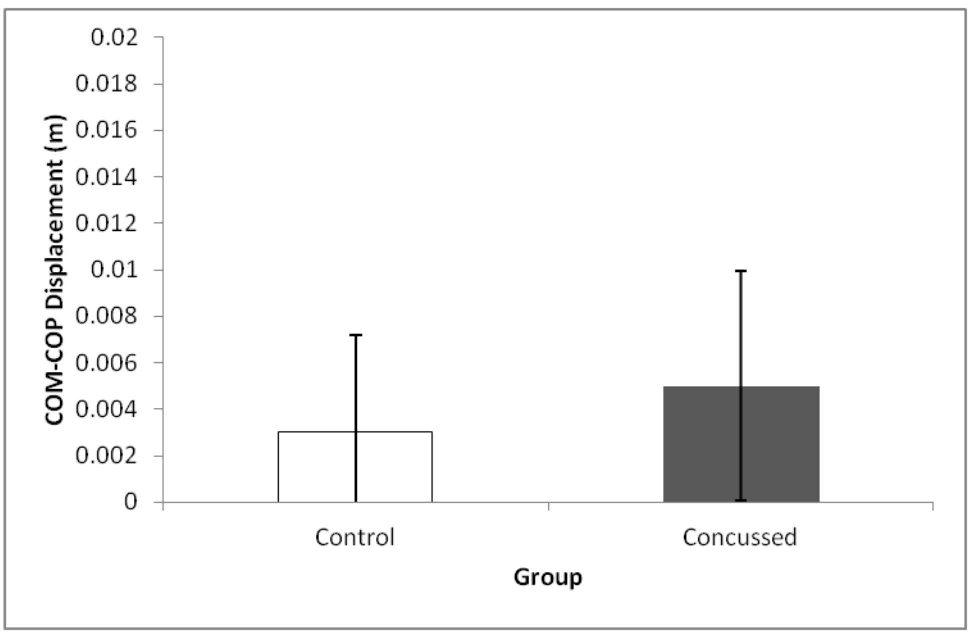

Figure 4a: Mean CONT and CONC groups' minimum COM-COP displacement collapsed across three Stepping Directions during Unloading phase. Not the significant increase in concussed COM-COP displacement compared to CONT. No significant differences in A/P COP displacement variability (p<0.05).

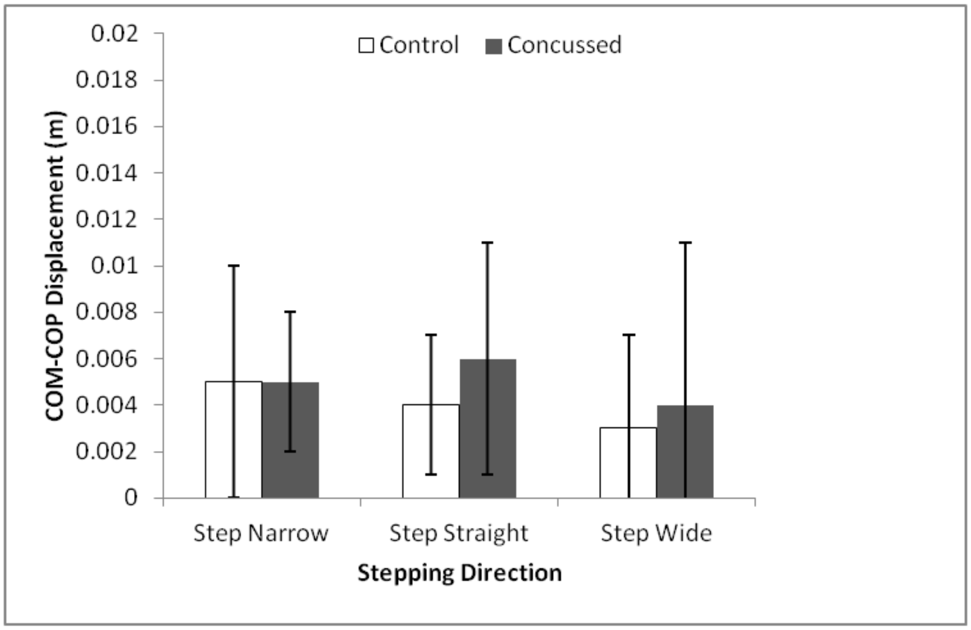

Figure 4b: Mean Minimum COM-COP Displacement separated by Stepping Direction and Group during Unloading. No significant interaction or variability effects.

<u>COM Movement Range (m)</u>

Table 5 shows the means and CoV of the M/L COM range displacement separated by stepping direction and CONT and CONC group.. The results revealed a significant main effect of Group (Control, M= 0.011; Concussed, M=0.017) whereby the Concussed group demonstrated a significant increase in M/L COM range displacement when compared to the Control group ($F_{(1, 41)}$ =5.812, p=0.02, r=0.139) (Figure 5a). However, there were no significant interaction effects of the M/L COM range displacement ($F_{(1.228, 50.345)}$= 0.995, p=0.340).

The results of the CoV of the M/L COM range displacement revealed that there was neither a significant Group effect ($F_{(1, 42)}$ =0.232, p=0.633) (Control, CoV=1.258; Concussed CoV=1.179) nor an interaction effect ($F_{(2,84)}$=1.156, p=0.320).

Table 5: Overall mean and coefficient of variation (CoV) values of M/L COM Range Displacement(m) for the CONT and CONC groups across each Stepping Directions.

Stepping Direction	Control (Mean)	Concussed (Mean)	Control (CoV)	Concussed (CoV)
Step Narrow	0.005	0.010	0.998	1.081
Step Straight	0.003	0.004	1.008	1.23
Step Wide	0.026	0.036	0.836	0.694

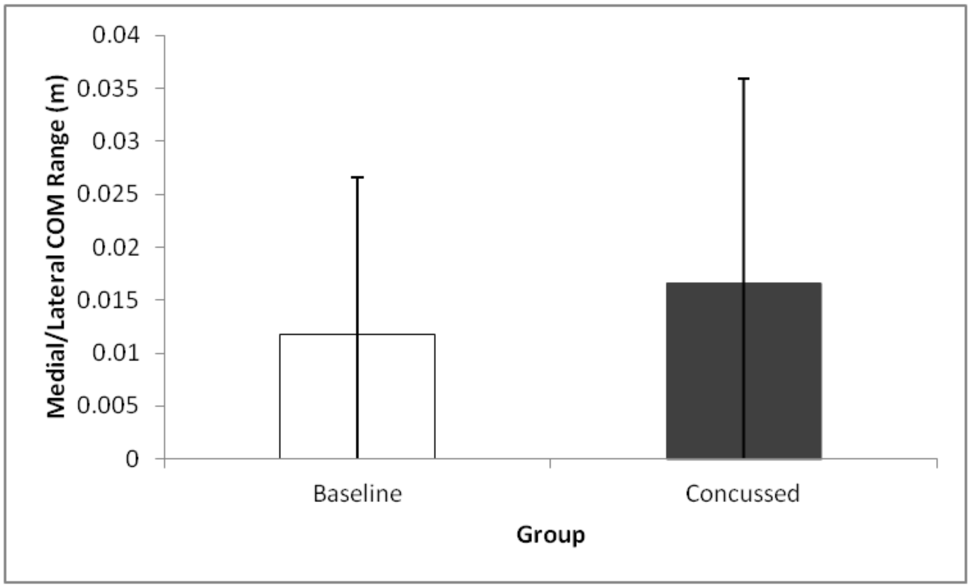

Figure 5a: Mean Medial/Lateral COM range displacement for both the CONT and CONC groups collapsed across Stepping Direction. Indicates that the manipulating variable in the COM-COP displacement is the COM. Mean M/L COM range displacement was significant higher in the CONC compared to CONT. No significant differences in M/L COM range displacement variability ($p<0.05$).

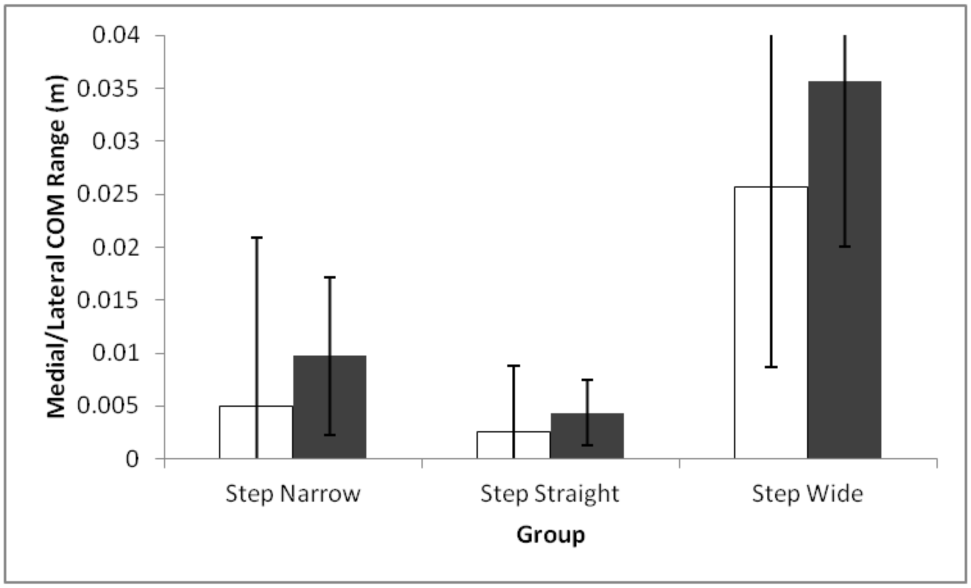

Figure 5b: Mean Medial/Lateral COM range displacement separated by Stepping Direction and Group during Unloading. No signficant interaction or variability effects

4.3 *End Phase*

To complete the analysis of gait imitation *End* phase measures must be examined to determine whether any excessive moments of force generated during the *Loading* phase could successfully be arrested by the *End* phase. Step length, swing time, and final foot placement (step width) were analyzed to determine whether increased propulsion in the loading phase reflects a change in behavior at the *End* phase. It was postulated that a significant increase in posterior COP displacement during the *Loading* phase would cause a significant increase in step length and a significant increase in swing time in the CONC group. Additionally, there would be a significant increase in final foot placement variability in the CONC group.

Swing Time (s)

Table 5 shows the means and CoV of Stepping Direction by Group for swing time duration in seconds. The results for mean swing time revealed there was a significant main effect of Group (Controls, M= 0.733s; Concussed, M=0.511s) where the Control group had a significantly longer swing time in comparison to the Concussed group ($F_{(1,44)}$=9.766, p=0.003, r=0.150) (Figure 6a). Additionally, there was no significant interaction effect of Group by Stepping Direction for swing time ($F_{(1.508, 66.362)}$=0.014, p=0.965) (Figure 6b).

The results for CoV indicate that there was no significant main effect of Group (Controls, CoV=0.153; Concussed, CoV= 0.179) ($F_{(1,44)}$=1.388, p=0.245). However, the results did reveal a significant interaction effect ($F_{(1.692, 74.453)}$= 3.370, p=0.047). Post-hoc analysis revealed that the Step Wide condition demonstrated a larger CoV for the Concussed group in comparison to the Control group (Table 6).

Table 6: Overall mean and coefficient of variation (CoV) values of Swing Time (s) for each the CONT and CONC groups across each Stepping Directions.

Stepping Direction	Control (Mean)	Concussed (Mean)	Control (CoV)	Concussed (CoV)
Step Narrow	0.736	0.510	0.181	0.161
Step Straight	0.733	0.512	0.162	0.182
Step Wide	0.730	0.510	0.117	0.194

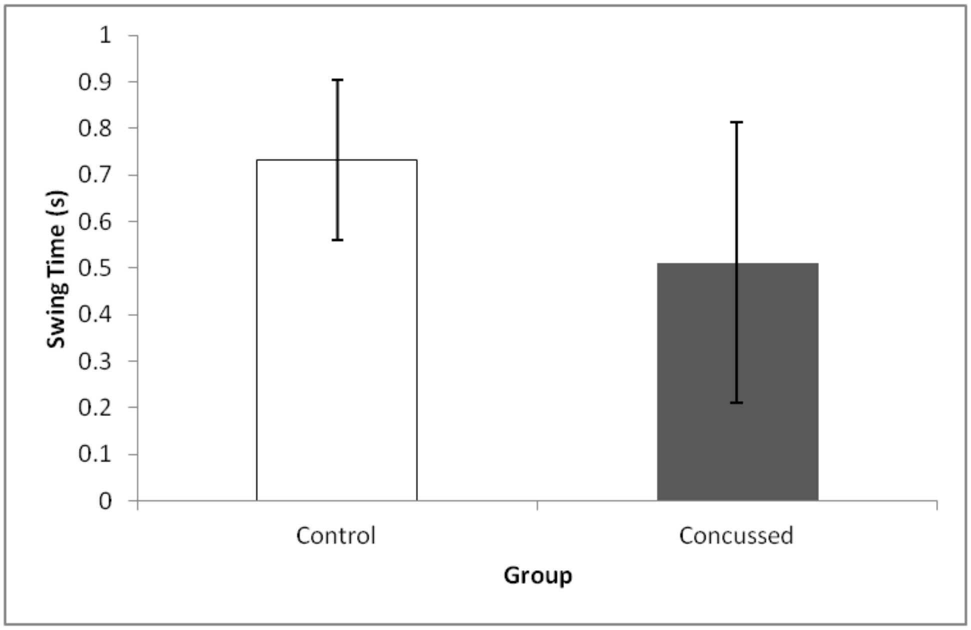

Figure 6a: Mean Swing Time for the CONT and CONC groups collapsed across three Stepping Directions. Mean Swing Time was significantly decreased in the CONC compared to CONT. Indicates that the swing limb spent significantly less time not in contact with the ground and less time in single support for the stance limb No significant differences in swing time variability ($p<0.05$).

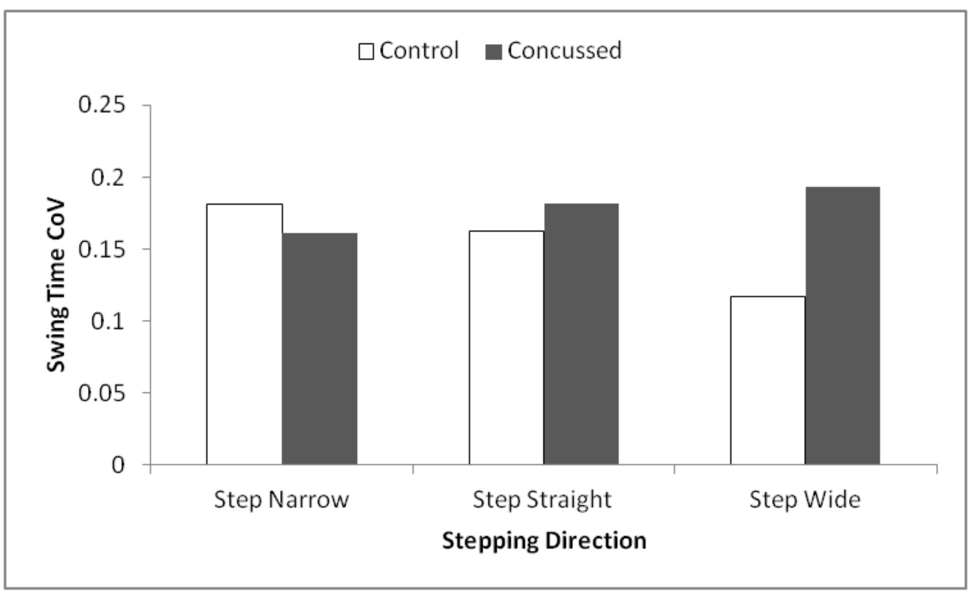

Figure 6b: Mean swing time CoV separated by Stepping Direction and Group. No significant differences in variability.

Normalized Step Length

Table 7 shows the means and CoV of Stepping Direction by Group for normalized (to body height) step length. The results for the mean normalized step length revealed that there was a significant main effect of Group (Control, M= 0.320; Concussed, M=0.395), where the Concussed group stepped a significantly longer than the Control group ($F_{(1,44)}$=11.659, p=0.001, r=0.394) (Figure 7a). There was no significant interaction effect of Stepping Direction by Group ($F_{(1,88)}$= 2.239, p=0.113) on normalized step length (Figure 7b).

The results for CoV of the normalized step length indicated that there was neither significant Group effect (Control, CoV=0.069; Concussed, CoV=0.062) ($F_{(1,43)}$=0.204, p=0.654) nor an interaction effect ($F_{(2,86)}$= 0.390, p=0.678).

Table 7: Overall mean and coefficient of variation (CoV) values of Normalized Step Length for the CONT and CONC across each Stepping Directions.

Stepping Direction	Control (Mean)	Concussed (Mean)	Control (CoV)	Concussed (CoV)
Step Narrow	0.314	0.381	0.065	0.075
Step Straight	0.327	0.410	0.078	0.053
Step Wide	0.320	0.396	0.066	0.058

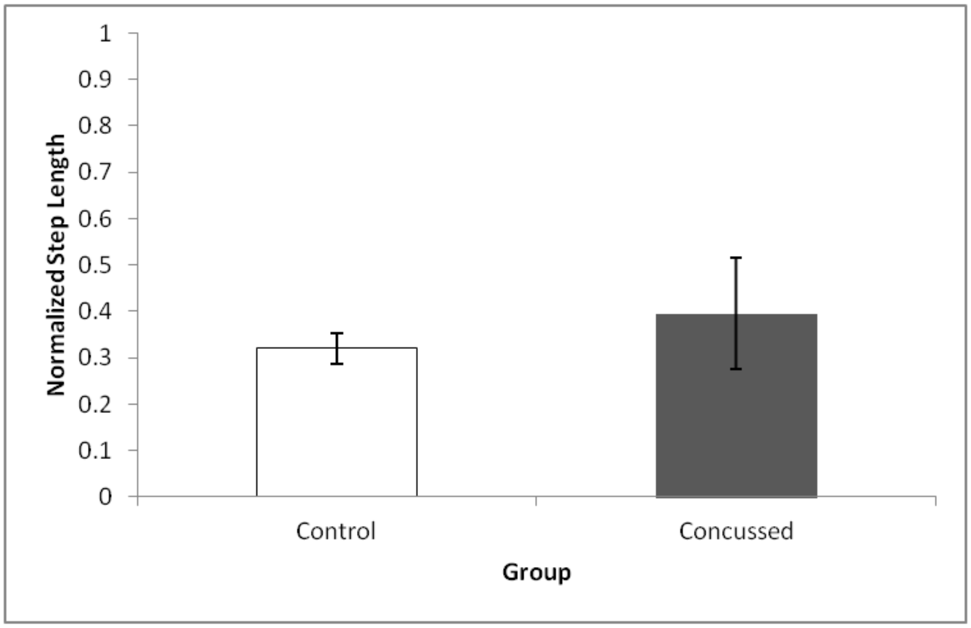

Figure 7a: Mean normalized Step Length collapsed across three Stepping Directions for the CONT and CONC groups. Mean Normalized Step Length was significantly increased in the CONC compared to CONT indicating a need to arrest COM momentum. No significant differences in swing time variability ($p<0.05$)

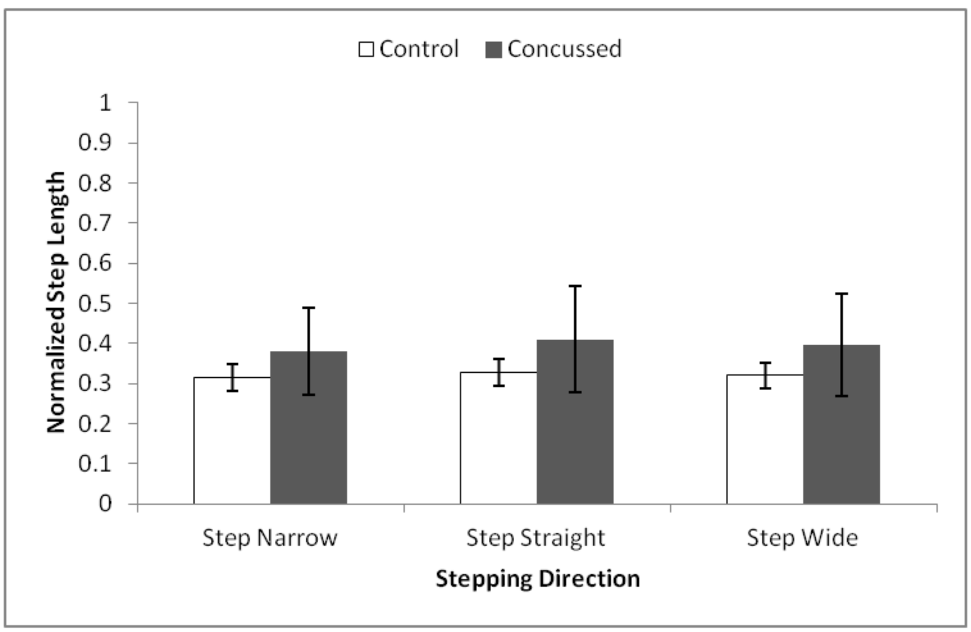

Figure 7b: Normalized Step Length separated by Stepping Direction and Group. Note in the CONC group that normalized step length increase across all stepping directions, No significant interaction or variability effects.

Final Foot Placement Measures

The results for mean final M/L foot displacement variability indicated that there was neither a main effect of Group ($F_{(1,46)}$=0.151, p=0.699) nor an interaction effect ($F_{(1.415,\ 65.069)}$= 0.558, p=0.516).

Additionally, the results indicated there was neither a main effect of Group on mean peak velocity ($F_{(1,43)}$=1.147, p=0.290) nor a significant interaction effect between Group and Stepping Direction ($F_{(1.552,\ 66.757)}$=1.320, p=0.269). As well, there was no main effect of Group on peak velocity as a percentage of swing time ($F_{(1,43)}$= 0.486, p=0.490) and no interaction effect between Group and Stepping Direction ($F_{(2,86)}$=1.675, p=0.193).

The results for peak velocity CoV indicated that there was no main effects of Group ($F_{(1,43)}$=0.145, p=0.706). The results from the CoV of peak velocity as a percentage of swing time also revealed that there was no significant main effect of Group ($F_{(1,43)}$=0.001, p=0.982). The results also revealed that there were no significant interaction effects for either peak velocity ($F_{(1.623,\ 69.789)}$=1.964, p=0.156) or peak velocity as a percentage of swing time ($F_{(1.180,\ 50.760)}$=0.065, p=0.839).

COM velocity (m/s) throughout movement

Mean velocity of A/P COM movement revealed that there was no main effect of Group (Control= 0.013m/s; Concussed =0.012m/s) ($F_{(1,43)}$=0.035, p=0.853) (Figure 7a). No interaction effect of Group by Stepping Direction ($F_{(1.009,\ 43.397)}$= 0.210, p= 0.651).

Results for CoV of the velocity of COM throughout the trial did not exhibit a main effect of Group (Control=0.152; Concussed= 0.1) ($F_{(1,43)}$ = 0.618, p=0.436). There was no interaction effect of Group by Stepping Direction ($F_{(1.723,\ 74.093)}$= 0.367, p=0.662).

5 Discussion

The objective of this study was to quantify stability following a concussion during a gait initiation task, which is an internal perturbation. It was hypothesized that the use of a fundamental task such as gait initiation would provide a more sensitive and objective measure of balance control changes following a concussion. Gait initiation was split into three distinct phases (i.e., loading, unloading, end phase) in order to provide insights to balance control deficits following the acute phase of a concussion.

5.1 *Loading phase*

Through the examination of the three phases of gait initiation the full expression of concussion-related motor deficits becomes clearly evident. Previous research has demonstrated significant changes in the M/L displacement of the COP during the loading phase for individuals with Parkinson's disease (Halliday et al., 1998; Martin et al., 2002) as well as with older adults (Halliday et al., 1998; Woollacott & Tang, 1997). However, the current study did find differences between the concussed and non concussed athletes; however the findings did not demonstrate similar increases in M/L displacement of the COP of the Concussed group (CONC) during the loading phase (Figure 1). This finding suggests that the nature of the deficits to balance control and gait initiation observed in individuals following a concussion are not the same as those observed in individuals with Parkinson's disease or with older adults. This study further outlined that the temporal and spatial patterns of gait initiation are preserved in PD as with younger adults albeit at a slower pace. The key distinguishing features of gait initiation in PD mentioned above do not appear to be exhibited by the CONC group in the current study. Therefore it is reasonable to assume that the behavior of the COP in the CONC group is not comparable to the deficits found in Parkinson's disease. It is important to note that the PD and CONC groups represent two different neurological problems that use two different compensatory strategies to prevent destabilization during gait initiation. Although some comparisons can be drawn between each group, overall they are unrelated in terms of their approach to gait initiation and the strategies they use. An analysis of PD in regards to gait initiation provides crucial information in the understanding of how the CONC group behaves. Since the PD group does not behave the same as the CONC group it can be assumed that the areas of the CNS affect by PD are not the same as those affect by a concussion.

The findings from the current study did demonstrate that there was a significant increase in posterior displacement of the Centre of Pressure (COP) in CONC when compared to the Control group (CONT) (Figure 2). This increase in COP displacement is a concern because an increased propulsive ground reaction force is needed to offset this increase in COP displacement and propel the Centre of Mass (COM) forward to initiate gait. Multiple studies have shown that during static stance, CONC individuals exhibit significant deficits in balance control (Cavanaugh et al., 2006; Guskiewicz, Perrin, & Gansneder, 1996; Guskiewicz, 2001; Powers, Kalmar, & Cinelli, 2013). Studies by Guskiewicz and colleges (1996; 2001) further demonstrated that these static balance control deficits manifest as increases in sway in unspecified directions. However they concluded that balance control measurements are a useful tool for analyzing concussions. More recently, Powers and colleges (2014) found that during quiet standing (i.e., static balance) there was a significant increase in the anterior-posterior (A/P) COP displacement and velocity when vision was removed during the acute phase following a concussion in comparison to non-concussed athletes. The authors suggest that these differences in A/P COP displacement and velocity between the groups were most likely due to vestibular nuclei impairments inherent to concussions. Taking this into consideration, it is probable that the concussed athletes in the current study would have exhibited similar increases in A/P COP displacement and velocity during static balance prior to gait initiation. Unfortunately, the current study did not measure static balance for a sufficient duration prior to gait initiation to accurately quantify static postural control.

During static stance, a change in COM behavior demands a change in the behavior of the COP due to the fact that the COP controls the COM. The increased frequency of COM oscillations creates instability during static stance because the CNS is unable to properly assess the amount of force needed to generate the proper ground reaction forces to control balance. This is reflected in greater COP excursions throughout stance (Jian, Winter, Ishac, & Gilchrist, 1993; Winter, 1995). Since previous research has demonstrated increases in COP and COM displacements in concussed individuals during stance, it is possible that the increased posterior displacement of the COP of the CONC during the loading phase in the current study is a reflection of the need to overcome this instability and initiate gait.

The transition from static balance state to the loading of the swing limb (i.e., *loading phase)* was considered to be the anticipatory postural adjustment (APA) phase of gait initiation and requires strict motor control. Bouisset and colleagues (2001) found that APAs were affected by the impending movement, such that amplitude and duration of muscle activation was proportional to the type of movement (i.e., greater activation for phase change from a static to dynamic state as in gait initiation). The areas of the brain thought to contribute to the refinement of control and execution of APAs were the premotor area, supplementary motor area (SMA), and the basal ganglia (Massion, 1992) and later included the cerebellum (Mori, Matsuyama, Mori, & Nakajima, 2001). Therefore, damage to any or all of these areas would result in changes to the control and/or execution of the APA. Previous research assessing gait initiation difference between individuals with Parkinson's disease (damage to basal ganglia) and age-matched individuals has demonstrated larger ML displacement of the COP during the APA phase of gait initiation (Bloem, van Vugt, & Beckley, 2001; Halliday et al., 1998). Conversely, the current study found that athletes with concussion displayed greater posterior COP displacement during APA (Figure 2a). Collectively, these two studies indicate that one of the aforementioned brain areas must be able to adapt the APA strategy in order to overcome the direction of greatest balance impairment (i.e., ML for individuals with PD and AP for individuals with concussions) and initiate gait. It is likely that it is not the basal ganglia that shapes the APA strategy, but rather one of the other 2 areas. Previous research has suggested that the premotor cortex projects directly into the spinal cord and is thought to have a direct role in behavior, specifically the planning of movement (di Pellegrino et al., 1992; Halsband et al., 1993), making it a likely candidate to shape the APA. In addition to contributions of the premotor cortex, the posterior parietal cortex (PPC) plays a important complimentary role in the production of planned movements (Andersen & Bueno, 1989). Before a movement can be initiated, the CNS requires specific information about the position and orientation of the body part used in the movement as well as the position of environmental objects that the body will interact with. The PPC plays a key role in guiding specific movements of the body while interpreting different sensory inputs (Andersen & Bueno, 1989). If the CONC group experienced any level of damage or impairment then a variety of sensorimotor deficits could present themselves. On the other hand, the SMA and cerebellum are thought to control the movement (Roland, Larsen, Lassen, & Skinhøj, 1980) the coordination, and the precision over movement (Ghez & Fahn, 1985). The SMA enacts the motor plan produced in the premotor cortex while the cerebellum is not involved in the initiation of movement. Therefore, during gait initiation, it would most likely be the premotor cortex that would serve to properly organize the goal-directed movement and any changes to the activation levels of this area would be apparent exclusively during the APA phase (i.e., loading profiles) (Jahn et al., 2004). In CONC it is probable that a concussive insult to the brain could have caused damage in the supplementary motor area affecting their ability to elicit the needed movement to overcome static instability in the A/P direction. The disparity between the loading phase in the CONC and CONT groups does not appear to exist in the premotor cortex but may be directly related to the ability to enact the needed muscular generation through the supplementary motor area (SMA); leading to change observed in the posterior COP displacement.

Feedback from proprioceptive and somatosensory sensory sources shape and mold the response of the CNS to the momentum of the COM generated during the loading phase of gait initiation (Cohen & Boothe, 1999; Halsband et al., 1993). Appropriate motor responses to perturbations of the CNS are highly dependent on external cues from the environment (Kuo, 2005; Peterka, 2002). The premotor cortex is used to plan the movement and the supplementary motor area is used to execute the given commands needed to prevent significant COM displacement. Therefore sensory feedback is highly important in the planning of motor responses to stimuli. Powers and colleges (2014) suggested that changes in COP displacement could be the direct result of impairment in the vestibular system. During the anticipatory phase of gait initiation (loading), significant increases in anterior COP displacement could be the direct result of vestibular impairment due to concussion. Not only are CNS functions interrupted but sensory system feedback may be also compromised. Although Powers and colleges (2014) noted this phenomenon in static stability tests, the changes in COP displacement are prior to initiation during the anticipatory phase. It is reasonable to assume that during the short transition from static to dynamic movement that vestibular deficiencies are still apparent.

5.2 *Unloading Phase*

During this subsequent phase of gait initiation, there were continued residual effects from the loading phase that presented themselves. In order to demonstrate these residual effects a series of assessments were performed to analyze the relationship between the COM and COP. The COM-COP relationship was analyzed during the unloading phase in an effort to clarify the manner in which stability has adapted during the transition phase between the loading and end phases. When analyzing the unloading phase, the COM-COP relationship provides clarity about the behavior of the COM as it relates to the COP, especially during the unloading phase when the COM is in close proximity to the COP. Previous studies using a COM-COP relationship suggested that the COM-COP relationship provides better analysis on balance then analyzing each variable independently (Hass et al., 2005a; Winter, 1995). Therefore with that in consideration, the COM-COP analysis revealed that there is a change in the minimum COM-COP displacement as unloading unfolds. These effects were not observed in maximum M/L COM-COP displacement measures (Figure 3), they were, however, observed in the minimum M/L COM-COP displacement measures (Figure 4) between the CONT and CONC groups. The greatest separation between the COM and COP (maximum) occurred at the start of the unloading phase and the smallest separation (minimum) occurred as the phase progressed. The fact that there was no difference in the M/L COP displacements between the two groups during the loading phase and no difference in the maximum M/L COM-COP displacement (start of unloading) suggests that both groups controlled their trunk (i.e., COM) in the M/L plane similarly during the beginning of this phase of gait initiation. Further analysis revealed that during the transition from the loading phase and unloading phase, the behavior of the COP also remained unchanged between groups. However, the COM range throughout the unloading phase was shown to significantly increase between groups and therefore acted as the manipulating variable in the COM-COP relationship. Since the COM-COP displacement does not vary at the maximum displacement, it is reasonable to assume that the behavior of the CONC and CONT groups remain unchanged in the M/L direction. In other words, how the CONC and CONT groups transition to the unloading phase from the loading phase remains consistent between groups, indicating that any changes that occurred during the unloading phase occur subsequent to this event.

Following a concussion, it is possible that the CONC group experiences changes in developing proper neural drive within the motor cortex and specifically, supplementary motor area, to activate the proper muscle synergies and adjust the force required to initiate gait in a normal manner. The appropriate neural drive for this develops in the premotor cortex during the loading phase and executed through the SMA. This action plan is observed during the unloading phase of initiation and is represented by the lack of destabilization. This indicated that during the unloading phase there does not appear to be any issues with the execution of motor commands developed within the SMA. The SMA is successfully able to initiate muscle synergies in such a way that the force generated in the M/L plane prevents destabilization. The development of an unloading-specific neural command occurred before the initiation of gait, indicating that the gait initiation effects developed during motor planning will not arise until the subsequent phases of gait initiation.

However, as the unloading phase progressed, the difference between the two groups' minimum M/L COM-COP displacements emerged (Figure 4). The minimum M/L COM-COP displacement is an indirect measure of dynamic stability during gait initiation. Using the M/L COM-COP displacement relationship can determine the proximity of the COM to the COP. When the COM and COP are in close proximity it is usually indicative of a decrease in dynamic stability (Corriveau et al., 2001).The findings from the current study demonstrate that this minimum M/L COM-COP displacement was greater in the CONC than the CONT (Figure 4). There are three possible ways in which this difference between the groups could have occurred: 1) COM movement or relative location was the same between groups but the COP moved less; 2) COM moved less while the COP was the same; or 3) COM moved more and the COP moved less. It is most probable that the increase in minimum M/L COM-COP displacement observed was the result of a decrease in the magnitude change of the M/L COM displacement for the CONC during the unloading phase (Figure 5a). Changes in M/L COM displacement during the loading phase would directly impact gait initiation through unloading and especially during the end phase. A reduction in the displacement between the COM and the COP may indicate an increase in stability due to an enhancement of compensatory strategies (i.e., stiffening). Individuals with a concussion do not experience excessive instability but rather excessive prevention of instability. Therefore other factors may be contributing to the maintenance of stability. One possibility, suggested by numerous studies, could be the use of an ankle strategy that could prevent destabilization through a stiffening approach achieved by co-contraction of the lower limb musculature (Ishikawa, Miyakoshi, Kasukawa, Hongo, & Shimada, 2009; Sims & Brauer, 2000). According to Ishikawa et al (2009), if the COM and the COP move along the same vertical lines, postural stability can be reestablished or maintained using an ankle strategy. In the current study, the CONC group was able to maintain stability during the loading phase of initiation as a method needed to overcome the inherent postural instability present during static stance. This may be possible through the implementation of the same ankle strategy used in the healthy CONT group. This type of strategy has been observed in balance compromised populations such as older adults and individuals with Parkinson's disease (Halliday et al., 1998; Winter, 1995) (Figure 9)

In a balance compromised population, excessive forward COM propulsion in the A/P direction would place greater demands on stability in the sagittal plane of movement.

Therefore movement of the COM in the M/L plane should not be affected by A/P COP displacement increases. However, the CNS is more cautious, as evidenced by a greater COM-COP displacement, indicating a purposeful but unconscious isolation of movement in the sagittal plane. In the current study the CONC group may be reducing the degrees of freedom about the ankle and hip joints in an effort to allow greater control of the movement by constraining it exclusively to sagittal plane. This is evidenced through a detailed analysis of the movement of the COM and COP during the unloading phase. At the maximum COM-COP displacement difference there was no difference in the location of the COM or COP between the groups and so there was no change in behaviors. However, during the minimum COM-COP displacement difference there was an increase in the COM range between the groups, indicating a limited M/L movement of the COM in the CONC group. The CNS must have restricted the degree of freedom within the movement, forcing the COM to move in the A/P direction with minimal M/L movement. This occurred in order to maintain M/L stability and force compensatory mechanisms to be enacted in the end phase.

The most common explanation for the CONC group to maintain stability is that the same stiffening strategy that was being used to prevent destabilization during the loading phase of gait initiation was being employed during the unloading phase. It is likely that this strategy was employed throughout gait initiation to prevent destabilization while allowing gait initiation to occur seamlessly. Most importantly, the movement of both groups' COM occurred in the direction of intended forward movement. These actions could suggest that even though gait initiation is a cortically driven activity, it can be modulated by sensory feedback (D'Hondt et al., 2011; Peterka, 2002). It is reasonable to assume that during the unloading phase there was minimal sensory dysfunction whereby stability was retained but preventative measures emerged to force all movement anteriorly in the A/P plane.

5.3 *End Phase*

The end phase of gait initiation is represented by the time between toe-off and heel-contact when the swing limb moves. The CONC group stepped significantly further and in a shorter time frame than the CONT group (Figure 6a & 7a). The increase in step length was thought to be the direct consequence of an increase in posterior displacement of the COP during loading phases. The prevention of M/L COM movement during the loading and unloading phases resulted in the COM being propelled forward in the A/P direction in both the CONT and CONC groups. However, the COM of the CONC group was more tightly controlled as indicated by a restriction in the M/L COM range. The stiffening strategy thought to be responsible for this isolated COM movement may have been used to compensate for COM instability during the end phase of gait initiation. This approach could be successful in preventing destabilization as stiffening the lower limb musculature could restrict COM movement and force the movement to occur only in the A/P plane of movement. This could have been accomplished by restricting the lower limb degrees of freedom to prevent COM movement in the M/L direction and ensuring that all movement occurred in the A/P direction. The results did not demonstrate any significant difference in the peak velocity of the swing limb during the end phase of gait initiation nor were there any statistical differences in the velocity of the COM. This suggests that COM velocity and peak velocity of the swing limb was unaffected by a concussive insult to the head. The movement outlined in the experiment would not yield significant changes in COM velocity as the entirety of the movement is mostly concentrated to the lower limbs. As gait initiation progresses through to toe off, there is not much of a change in COM velocity as the COM does not displace with any significance from its starting position. Therefore there would be minimal impact on the COM velocity in this particular movement. It is however surprising that there was no noticeable difference in the peak velocity of the swing limb. In order to examine these trends future research should employ a 2 to 4 step gait initiation paradigm.

One noticeable difference between the CONC and the CONT group was a significant decrease in swing time in the CONC group during the end phase of movement. This is indicative of another potential strategy to prevent destabilization as a decrease in swing time in the concussed group would decrease the amount of time the COM is in single support. Single support phase of stance is highly unstable because the COM is located outside the BOS. As such, it is likely that the CNS would want to restrict the amount of time that an unstable individual (i.e., CONC) spends in that phase. By reducing the time spent in single support, there is a decreased likelihood of a fall or compensatory step that is not in the plane of movement (Winter, 1995). Once an athlete is concussed, he or she exemplified an appropriate adaptation strategy to recover the increase in COM momentum developed from the increased COP posterior displacement during the loading phase. The increased step length and decreased swing time of the swing limb is a neurological response to arrest this increased COM momentum developed during the loading phase and prevent instability respectively (Andriacchi, Ogle, & Galante, 1977; Winter, 1995). However, an increased step length would normally indicate an increased time in single support but the recognition of swing time increases negates that. These factors would normally indicate decrease in gait stability but rather this represents the same strategy of gait conservation. By increasing the step length and decreasing swing time, conservation of gait in maintained as these could be compensatory mechanisms that balance-compromised individuals employ to maintain stability. The combination of increased step length and decreased step time in the concussed population used the mechanical force generation of the legs to catch the COM by initiating a force event opposing the increased momentum of the COM. The strategy employed by the CNS to overcome postural instability of the CONC group during quiet stance and effectively produce gait initiation was most likely developed within the premotor cortex. The end product of this strategy was excessive propulsive force acting on the COM creating an increased momentum which appears to be successfully corralled by the swing limb.

These strategies represent a selection of motor responses to a specific problem. The nature of the moment (degrees of freedom) elicits a specific type of response. The current study restricted participants' movements to only a single step, preventing high variability. There are two types of strategies needed to counter a perturbation: a "fixed-support" strategy and a "change-in-support" strategy (Maki & McIlroy, 1997). The participants in the current study only employ a "change-in-support" strategy and therefore compensatory strategies employed a lower limb movement to prevent destabilization. During gait initiation, the CONC group used the swing limb to compensate for changes developed during the loading phase. The end phase represents the summation of these events that must be compensated for by using this strategy.

6 Conclusion

The initiation of gait is defined as the transition between standing motionless and steady-state locomotion (Rosin et al., 1997). The success of this type of motion is dependent on the successful integration of all the sensory systems, the CNS, and executing the appropriate motor responses to maintain stability. In normal healthy individuals, gait initiation is a stereotypical, efficient movement that requires minimum modulation. However when the system is compromised due to changes in either the sensory systems or motor systems as a result of ageing or disease, successful gait initiation maybe not be achievable. In the case of the concussed group (CONC), postural instability is a common symptom associated with a concussive injury. Multiple studies have noted that postural instability is a common symptom examined during static stability testing (Guskiewicz et al., 1996; Guskiewicz et al., 2001; Powers et al., 2013). These studies are insightful to understanding balance control issues following a concussion and their duration; however they are not representative of balance issues experiences during game or daily life. In order to address this limitation, more recent research has examined behavioral changes in stability during a dynamic activity (Martini et al., 2011; Parker, Osternig, Van Donkelaar, & Chou, 2006; Parker et al., 2008). These studies varied in levels of difficulty, which makes their findings difficult to generalize. The current study examined gait initiation, a challenging but yet common daily task in which an individual must perturb their body in order to transition from a stable static situation to a dynamic situation. Perturbations are the best method to test the stability of a system and gait initiations are a form of self-perturbations and should be stereotypical. The findings from the current study demonstrated that the CONC exhibited significant mechanistic differences during all three phases of gait initiation. The objective of this study was to better quantify stability measures following a concussion by using a functional task such as gait initiation in order improve on existing techniques used in concussion detection. It was hypothesized that the use of a functional task such as gait initiation will provide more sensitive and objective measures of balance control changes following a concussion. It was determined that measuring gait initiation in a concussed population would be successful in the detection and extricating of an individual who was suspected to have experienced a concussion. Additionally, it was demonstrated that a gait initiation task could successfully provide a more sensitive and objective measure of balance control in a compromised population such as those with a concussion.

In each phase, there were specific mechanisms used by the CONC to adapt to the deficiencies caused by a concussion or mild traumatic brain injury. During the *Loading Phase,* the excessive COP posterior displacement pushed the COM forward at a greater rate. Previous research has demonstrated that during the static phase prior to gait initiation there is a decrease in the stability of the COM in CONC that is uncommon in healthy individuals (Guskiewicz et al., 1996; Guskiewicz, 2001; McCrory et al., 2013; Powers et al., 2013). It is believed that instability during the static phase prior to gait initiation may have contributed to an increase in COP posterior displacement experienced during the *Loading Phase*. This instability would have been needed to overcome the previously reported increased A/P COM sway during the static phase. During the *Unloading Phase,* the COM-COP displacement was decreased in CONC. However, the COM always remained within the COP. This decreased displacement could have been due to a stiffening strategy that constrained the COM, forcing it to move anteriorly while tightly containing M/L displacement (Comerford & Mottram, 2001; Peterka, 2002; Winter et al., 1998). The *End Phase* of gait initiation represents the aggregation of behavior from the previous two phases of gait initiation. The CNS generated the necessary opposition forces needed to arrest excessive COM momentum in the A/P plane (Winter, 1995). This is a reactionary mechanism developed in CNS and modulated by somatosensory and proprioceptive feedback (Halliday et al., 1998; Powers et al., 2014). The end phase successfully corralled the COM and prevented destabilization that could have carried over into steady-state gait.

The techniques of the current study were developed to analyze a concussion through the implementation of a gait initiation task. Although the current study revealed some significant mechanical differences in control following a concussion, the findings do have restrictions on what they are able to evaluate in this population. Future studies should endeavor to build on this study and include some important changes. For instance, in order to gain better understanding of the COM during the loading phase, the static quiet standing phase or the anticipatory phase prior to gait initiation should be included. By recording this information, a better assessment can be made between the COM and COP behaviors prior to and during gait initiation. Powers and colleagues (2014) revealed that static stability testing was a sensitive enough measure to analyze athletes' postural control following a concussion and track the progression of the concussion. Even after athletes returned to play continued to display inherent instability during static stance (Powers et al., 2014). However, the transition from static stance to gait initiation provides a sequential analysis that may explain why changes occur in gait initiation and how they carry through the first few steps of gait (Winter, 1995).

In order to make inferences about specific strategies (e.g. Stiffening strategy) employed to prevent destabilization, EMG collection should be a priority. EMG would allow researchers to determine whether concussed individuals employ a stiffening strategy to maintain control of the COM, especially during the unloading phase of initiation. Studies by Sutherland (2001) and Bovi (2011) indicate that EMG recordings taken during gait are imperative to the understanding of the forces causing or helping with the movement. By measuring muscle activation activity predictions can be made in tandem with kinetic and kinematic data regarding the behavior of the entire body during gait initiation. By incorporating these additional sources of information along with muscle activation would allow for the analysis of the strategy being employed.

Finally, participants in the current study were restricted to only a single step during the initiation of gait. By allowing participants to continue walking over 3 to 4 steps post-initiation could yield differences in behavior. In a study by Muir and colleagues (2014) the authors examined the differences in gait initiation characteristics across healthy populations aged 20-25, 65-79, and 80-91 years of age. Subjects were required to stand and once initiated by a visual command, walk at a self-selected pace over an area of 3.2m from the start position. Six trials were unobstructed and the remaining trials required participants to step over a stationary obstacle in the middle of the pathway. Step length and step width were significant decreased across all ages. It was noted however that gait speed is controlled by older adults in the same manner as young adults. The authors also noted high variability in step length and step width which could indicate a decrease in dynamic stability of the COM. Finally, the authors indicated following successive steps that A/P COM control improves while M/L COM control decreases across all age groups. As age increases, gait stability preservation became a higher priority as indicated by gait speed and step length decreasing as age increased (Muir et al., 2014). However, gait speed control was not compromised with age. Muir and colleges (2014) concluded that successive steps in A/P COM control improves in young individuals and that M/L COM control declines in all age groups. Using the paradigm outlined by Muir and colleges (2014), analysis of gait initiation in a concussed population using multiple steps post-initiation may demonstrate that a concussed population behaves more like older adults or somewhere on the spectrum of COM recovery. The current study is limited in understanding how the observed changes during gait initiation translate to gait changes during steady state gait. Enabling a paradigm such as this may change the anticipatory behavior of the COM and COP prior to gait initiation as engaging in steady state locomotion may require different initiation mechanisms. These changes observed during concussion examination may provide a more insightful knowledge into the effects of a concussion on gait initiation.

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8 Appendix

8.1 Appendix A

MEDICAL INFORMATION

LAST NAME: ______________________________ FIRST NAME: _________________________

LOCAL ADDRESS: _________________________________ CITY, PROV. _________________

PHONE: __________________ EMAIL ADDRESS: ____________________

BIRTH DATE: ____________________________

Musculoskeletal Injuries:

- Have you sustained a fracture (broken bone) anywhere in your body?
  Yes ☐ No ☐
  If yes, please explain the location of fracture and when it occurred
- Have you sustained an injury to the following:
  Hip Yes ☐ No ☐
  If yes, please explain

  Knee Yes☐ No ☐
  If yes, please explain

  Ankle Yes ☐ No ☐
  If yes, please explain

- Have you had any surgery?
  Yes ☐ No ☐
  If yes, please explain the surgery and when it occurred
- Have you experienced vertigo / balance problems?
  Yes ☐ No ☐
  If yes, please explain

- Have you ever fainted or lost consciousness during exercise?
  Yes ☐ No ☐
  If yes, please explain

- Have you had any previous injuries to the neck or face?
  Yes ☐ No ☐
  If yes, please explain

- Have you ever had a concussion?

Yes □ No □

If yes how many?
When was your last concussion?
Have you ever lost consciousness?

Yes □ No □

If yes, for how long?
Have you ever been kept out of sport / activity with a concussion?

Yes □ No □

- Please complete the chart below if you have ever experienced a concussion

Head Injury History (concussions)

Year	Sport / Activity	Unconscious Y / N	Hospitalized	Time off of activity

8.2 Appendix B.

WILFRID LAURIER UNIVERSITY
INFORMED CONSENT STATEMENT
Quantifying Balance Control in Concussed Varsity Athletes
Adam Harper (harp2900@mylaurier.ca) & Dr. Michael Cinelli (mcinelli@wlu.ca)

You are invited to participate in a research study. The purpose of this study is to employ a dynamic balance task to quantify existing clinical tools used to determine when an athlete is ready to return to play following a concussion. The study will be conducted by graduate thesis student, Adam Harper, and supervisor, Dr. Michael Cinelli from the Department of Kinesiology and Physical Activity at Wilfrid Laurier University.

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Dr. Michael Cinelli
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INFORMATION

The stepping test will require participants to stand on force platform with both feet touching while their arms are folded behind their backs. The force platform will be used to calculate the participants' control of their balance during a single step. A raised platform will be constructed around the participant at the level of the force platform for them to step on. Marked on the platform will be three foot targets; at 0° at 30° to the right, and 30° to the left. Participants will also be fitted with motion capture markers for analysis. Before individuals participate in the experimental protocol there will be three control trials performed. Following this pre-test, the participants will be required to take a single step from the standing position towards one of the three different targets with their dominant foot such that the participant will perform either a step wide, step narrow or cross-over step. Three LED lights will be placed at eye level to indicate which of the three targets the participant is required to step on. Baseline testing will take approximately 20 minutes. This will be repeated for a participant who has received a concussion at times outlined by the athletic therapist. Individuals will not be filmed for this experiment.

RISKS

Participants may experience some of the following physical risks: disorientation, light-headedness, reduction in the level of postural control, and general discomfort due to taking a single step in multiple directions using a step wide/step narrow approach. Participants may feel discomfort while the optokinetic markers are taped on the skin for the duration of the experiment.

BENEFITS

Although participants will experience possible disorientation and light-headedness, individuals will further the understanding of the relationship between concussions and loss of postural control. The results from each participant will aid in the construction of a more sensitive post-concussion test.

CONFIDENTIALITY

Participants will be kept anonymous using a numbering system that only the investigator, Adam Harper, and supervisor, Dr. Michael Cinelli will understand. Experimental data will be stored on the lab computers and then burned to a DVD. The data will then be deleted from the lab computers. The DVD containing the information will be kept for several years in the lab (NC-104) at Wilfrid Laurier Univeristy and then destroyed. Only the principal investigator and co-investigator will have access to the research information. Participants will not be identified in presentations or journal articles but rather using the numbering system.

CONTACT

If you have questions at any time about the study or the procedures, (or you experience adverse effects as a result of participating in this study) you may contact the researcher, Dr. Michael Cinelli at (519) 884-0710 x 4217 or Adam Harper at (519) 884-0710 x 4775. This project has been reviewed and approved by the University Research Ethics Board. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. Robert Basso, Chair, University Research Ethics Board, Wilfrid Laurier University, (519) 884-1970, extension 5225 or rbasso@wlu.ca

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study, every attempt will be made to remove your data from the study, and have it destroyed. You have the right to omit any question(s)/procedure(s) you choose.

FEEDBACK AND PUBLICATION

Participants will receive feedback in the form of a handout that will be provided to all teams. Information taken from this study will be published in journal articles and presented at conferences.

CONSENT

I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Participant's signature____ Date __________________

Investigator's signature_______________________________________ Date __________________

8.3 Appendix C

SCAT3™

FIFA

Sport Concussion Assessment Tool – 3rd Edition

For use by medical professionals only

Name

Date/Time of Injury:
Date of Assessment:

Examiner:

What is the SCAT3?[1]

The SCAT3 is a standardized tool for evaluating injured athletes for concussion and can be used in athletes aged from 13 years and older. It supersedes the original SCAT and the SCAT2 published in 2005 and 2009, respectively[2]. For younger persons, ages 12 and under, please use the Child SCAT3. The SCAT3 is designed for use by medical professionals. If you are not qualified, please use the Sport Concussion Recognition Tool[1]. Preseason baseline testing with the SCAT3 can be helpful for interpreting post-injury test scores.

Specific instructions for use of the SCAT3 are provided on page 3. If you are not familiar with the SCAT3, please read through these instructions carefully. This tool may be freely copied in its current form for distribution to individuals, teams, groups and organizations. Any revision or any reproduction in a digital form requires approval by the Concussion in Sport Group.

NOTE: The diagnosis of a concussion is a clinical judgment, ideally made by a medical professional. The SCAT3 should not be used solely to make, or exclude, the diagnosis of concussion in the absence of clinical judgement. An athlete may have a concussion even if their SCAT3 is "normal".

What is a concussion?

A concussion is a disturbance in brain function caused by a direct or indirect force to the head. It results in a variety of non-specific signs and/or symptoms (some examples listed below) and most often does not involve loss of consciousness. Concussion should be suspected in the presence of **any one or more** of the following:

- Symptoms (e.g., headache), or
- Physical signs (e.g., unsteadiness), or
- Impaired brain function (e.g. confusion) or
- Abnormal behaviour (e.g., change in personality).

SIDELINE ASSESSMENT

Indications for Emergency Management

NOTE: A hit to the head can sometimes be associated with a more serious brain injury. Any of the following warrants consideration of activating emergency procedures and urgent transportation to the nearest hospital:

- Glasgow Coma score less than 15
- Deteriorating mental status
- Potential spinal injury
- Progressive, worsening symptoms or new neurologic signs

Potential signs of concussion?

If any of the following signs are observed after a direct or indirect blow to the head, the athlete should stop participation, be evaluated by a medical professional and **should not be permitted to return to sport the same day** if a concussion is suspected.

Any loss of consciousness?	Y	N
"If so, how long?"		
Balance or motor incoordination (stumbles, slow/laboured movements, etc.)?	Y	N
Disorientation or confusion (inability to respond appropriately to questions)?	Y	N
Loss of memory:	Y	N
"If so, how long?"		
"Before or after the injury?"		
Blank or vacant look:	Y	N
Visible facial injury in combination with any of the above:	Y	N

1 Glasgow coma scale (GCS)

Best eye response (E)	
No eye opening	1
Eye opening in response to pain	2
Eye opening to speech	3
Eyes opening spontaneously	4
Best verbal response (V)	
No verbal response	1
Incomprehensible sounds	2
Inappropriate words	3
Confused	4
Oriented	5
Best motor response (M)	
No motor response	1
Extension to pain	2
Abnormal flexion to pain	3
Flexion/Withdrawal to pain	4
Localizes to pain	5
Obeys commands	6
Glasgow Coma score (E + V + M)	of 15

GCS should be recorded for all athletes in case of subsequent deterioration.

2 Maddocks Score[3]

"I am going to ask you a few questions, please listen carefully and give your best effort."

Modified Maddocks questions (1 point for each correct answer)

What venue are we at today?	0	1
Which half is it now?	0	1
Who scored last in this match?	0	1
What team did you play last week/game?	0	1
Did your team win the last game?	0	1
Maddocks score		of 5

Maddocks score is validated for sideline diagnosis of concussion only and is not used for serial testing.

Notes: Mechanism of Injury ("tell me what happened"?):

Any athlete with a suspected concussion should be REMOVED FROM PLAY, medically assessed, monitored for deterioration (i.e., should not be left alone) and should not drive a motor vehicle until cleared to do so by a medical professional. No athlete diagnosed with concussion should be returned to sports participation on the day of Injury.

BACKGROUND

Name: ______ Date: ______

Examiner: ______

Sport/team/school: ______ Date/time of injury: ______

Age: ______ Gender: M F

Years of education completed: ______

Dominant hand: right left neither

How many concussions do you think you have had in the past? ______

When was the most recent concussion? ______

How long was your recovery from the most recent concussion? ______

Have you ever been hospitalized or had medical imaging done for a head injury? Y N

Have you ever been diagnosed with headaches or migraines? Y N

Do you have a learning disability, dyslexia, ADD/ADHD? Y N

Have you ever been diagnosed with depression, anxiety or other psychiatric disorder? Y N

Has anyone in your family ever been diagnosed with any of these problems? Y N

Are you on any medications? If yes, please list: Y N

SCAT3 to be done in resting state. Best done 10 or more minutes post excercise.

SYMPTOM EVALUATION

3 How do you feel?

"You should score yourself on the following symptoms, based on how you feel now".

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6

Total number of symptoms (Maximum possible 22)

Symptom severity score (Maximum possible 132)

Do the symptoms get worse with physical activity? Y N

Do the symptoms get worse with mental activity? Y N

self rated | self rated and clinician monitored

clinician interview | self rated with parent input

Overall rating: If you know the athlete well prior to the injury, how different is the athlete acting compared to his/her usual self?

Please circle one response:

no different	very different	unsure	N/A

Scoring on the SCAT3 should not be used as a stand-alone method to diagnose concussion, measure recovery or make decisions about an athlete's readiness to return to competition after concussion. Since signs and symptoms may evolve over time, it is important to consider repeat evaluation in the acute assessment of concussion.

COGNITIVE & PHYSICAL EVALUATION

4 Cognitive assessment

Standardized Assessment of Concussion (SAC)[4]

Orientation (1 point for each correct answer)

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1
Orientation score		of 5

Immediate memory

List	Trial 1		Trial 2		Trial 3		Alternative word list		
elbow	0	1	0	1	0	1	candle	baby	finger
apple	0	1	0	1	0	1	paper	monkey	penny
carpet	0	1	0	1	0	1	sugar	perfume	blanket
saddle	0	1	0	1	0	1	sandwich	sunset	lemon
bubble	0	1	0	1	0	1	wagon	iron	insect
Total									

Immediate memory score total of 15

Concentration: Digits Backward

List	Trial 1		Alternative digit list		
4-9-3	0	1	6-2-9	5-2-6	4-1-5
3-8-1-4	0	1	3-2-7-9	1-7-9-5	4-9-6-8
6-2-9-7-1	0	1	1-5-2-8-6	3-8-5-2-7	6-1-8-4-3
7-1-8-4-6-2	0	1	5-3-9-1-4-8	8-3-1-9-6-4	7-2-4-8-5-6
Total of 4					

Concentration: Month in Reverse Order (1 pt. for entire sequence correct)

Dec-Nov-Oct-Sept-Aug-Jul-Jun-May-Apr-Mar-Feb-Jan 0 1

Concentration score of 5

5 Neck Examination:

Range of motion | Tenderness | Upper and lower limb sensation & strength

Findings:

6 Balance examination

Do one or both of the following tests.

Footwear (shoes, barefoot, braces, tape, etc.)

Modified Balance Error Scoring System (BESS) testing[5]

Which foot was tested (i.e. which is the **non-dominant** foot) Left Right

Testing surface (hard floor, field, etc.)

Condition

Double leg stance: Errors

Single leg stance (non-dominant foot): Errors

Tandem stance (non-dominant foot at back): Errors

And / Or

Tandem gait[6,7]

Time (best of 4 trials): ______ seconds

7 Coordination examination

Upper limb coordination

Which arm was tested: Left Right

Coordination score of 1

8 SAC Delayed Recall[4]

Delayed recall score of 5

INSTRUCTIONS

Words in *Italics* throughout the SCAT3 are the instructions given to the athlete by the tester.

Symptom Scale

"You should score yourself on the following symptoms, based on how you feel now".

To be completed by the athlete. In situations where the symptom scale is being completed after exercise, it should still be done in a resting state, at least 10 minutes post exercise.

For total number of symptoms, maximum possible is 22.

For Symptom severity score, add all scores in table, maximum possible is 22 x 6 = 132.

SAC[4]

Immediate Memory

"I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order."

Trials 2 & 3:

"I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before."

Complete all 3 trials regardless of score on trial 1 & 2. Read the words at a rate of one per second. **Score 1 pt. for each correct response.** Total score equals sum across all 3 trials. Do not inform the athlete that delayed recall will be tested.

Concentration

Digits backward

"I am going to read you a string of numbers and when I am done, you repeat them back to me backwards, in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7."

If correct, go to next string length. If incorrect, read trial 2. **One point possible for each string length**. Stop after incorrect on both trials. The digits should be read at the rate of one per second.

Months in reverse order

"Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November ... Go ahead"

1 pt. for entire sequence correct

Delayed Recall

The delayed recall should be performed after completion of the Balance and Coordination Examination.

"Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order."

Score 1 pt. for each correct response

Balance Examination

Modified Balance Error Scoring System (BESS) testing[5]

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)[5]. A stopwatch or watch with a second hand is required for this testing.

"I am now going to test your balance. Please take your shoes off, roll up your pant legs above ankle (if applicable), and remove any ankle taping (if applicable). This test will consist of three twenty second tests with different stances."

(a) Double leg stance:

"The first stance is standing with your feet together with your hands on your hips and with your eyes closed. You should try to maintain stability in that position for 20 seconds. I will be counting the number of times you move out of this position. I will start timing when you are set and have closed your eyes."

(b) Single leg stance:

"If you were to kick a ball, which foot would you use? [This will be the dominant foot] Now stand on your non-dominant foot. The dominant leg should be held in approximately 30 degrees of hip flexion and 45 degrees of knee flexion. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

(c) Tandem stance:

"Now stand heel-to-toe with your non-dominant foot in back. Your weight should be evenly distributed across both feet. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

Balance testing – types of errors

1. Hands lifted off iliac crest
2. Opening eyes
3. Step, stumble, or fall
4. Moving hip into > 30 degrees abduction
5. Lifting forefoot or heel
6. Remaining out of test position > 5 sec

Each of the 20-second trials is scored by counting the errors, or deviations from the proper stance, accumulated by the athlete. The examiner will begin counting errors only after the individual has assumed the proper start position. **The modified BESS is calculated by adding one error point for each error during the three 20-second tests. The maximum total number of errors for any single condition is 10.** If a athlete commits multiple errors simultaneously, only one error is recorded but the athlete should quickly return to the testing position, and counting should resume once subject is set. Subjects that are unable to maintain the testing procedure for a minimum of **five seconds** at the start are assigned the highest possible score, ten, for that testing condition.

OPTION: For further assessment, the same 3 stances can be performed on a surface of medium density foam (e.g., approximately 50 cm x 40 cm x 6 cm).

Tandem Gait[6,7]

Participants are instructed to stand with their feet together behind a starting line (the test is best done with footwear removed). Then, they walk in a forward direction as quickly and as accurately as possible along a 38mm wide (sports tape), 3 meter line with an alternate foot heel-to-toe gait ensuring that they approximate their heel and toe on each step. Once they cross the end of the 3m line, they turn 180 degrees and return to the starting point using the same gait. A total of 4 trials are done and the best time is retained. Athletes should complete the test in 14 seconds. Athletes fail the test if they step off the line, have a separation between their heel and toe, or if they touch or grab the examiner or an object. In this case, the time is not recorded and the trial repeated, if appropriate.

Coordination Examination

Upper limb coordination

Finger-to-nose (FTN) task:

"I am going to test your coordination now. Please sit comfortably on the chair with your eyes open and your arm (either right or left) outstretched (shoulder flexed to 90 degrees and elbow and fingers extended), pointing in front of you. When I give a start signal, I would like you to perform five successive finger to nose repetitions using your index finger to touch the tip of the nose, and then return to the starting position, as quickly and as accurately as possible."

Scoring: 5 correct repetitions in < 4 seconds = 1

Note for testers: Athletes fail the test if they do not touch their nose, do not fully extend their elbow or do not perform five repetitions. **Failure should be scored as 0.**

References & Footnotes

1. This tool has been developed by a group of international experts at the 4th International Consensus meeting on Concussion in Sport held in Zurich, Switzerland in November 2012. The full details of the conference outcomes and the authors of the tool are published in The BJSM Injury Prevention and Health Protection, 2013, Volume 47, Issue 5. The outcome paper will also be simultaneously co-published in other leading biomedical journals with the copyright held by the Concussion in Sport Group, to allow unrestricted distribution, providing no alterations are made.

2. McCrory P et al., Consensus Statement on Concussion in Sport – the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. British Journal of Sports Medicine 2009; 43: i76-89.

3. Maddocks, DL; Dicker, GD; Saling, MM. The assessment of orientation following concussion in athletes. Clinical Journal of Sport Medicine. 1995; 5(1): 32–3.

4. McCrea M. Standardized mental status testing of acute concussion. Clinical Journal of Sport Medicine. 2001; 11: 176–181.

5. Guskiewicz KM. Assessment of postural stability following sport-related concussion. Current Sports Medicine Reports. 2003; 2: 24–30.

6. Schneiders, A.G., Sullivan, S.J., Gray, A., Hammond-Tooke, G. & McCrory, P. Normative values for 16-37 year old subjects for three clinical measures of motor performance used in the assessment of sports concussions. Journal of Science and Medicine in Sport. 2010; 13(2): 196–201.

7. Schneiders, A.G., Sullivan, S.J., Kvarnstrom. J.K., Olsson, M., Yden. T. & Marshall, S.W. The effect of footwear and sports-surface on dynamic neurological screening in sport-related concussion. Journal of Science and Medicine in Sport. 2010; 13(4): 382–386

ATHLETE INFORMATION

Any athlete suspected of having a concussion should be removed from play, and then seek medical evaluation.

Signs to watch for

Problems could arise over the first 24–48 hours. The athlete should not be left alone and must go to a hospital at once if they:

- Have a headache that gets worse
- Are very drowsy or can't be awakened
- Can't recognize people or places
- Have repeated vomiting
- Behave unusually or seem confused; are very irritable
- Have seizures (arms and legs jerk uncontrollably)
- Have weak or numb arms or legs
- Are unsteady on their feet; have slurred speech

Remember, it is better to be safe.
Consult your doctor after a suspected concussion.

Return to play

Athletes should not be returned to play the same day of injury.
When returning athletes to play, they should be **medically cleared and then follow a stepwise supervised program,** with stages of progression.

For example:

Rehabilitation stage	Functional exercise at each stage of rehabilitation	Objective of each stage
No activity	Physical and cognitive rest	Recovery
Light aerobic exercise	Walking, swimming or stationary cycling keeping intensity, 70 % maximum predicted heart rate. No resistance training	Increase heart rate
Sport-specific exercise	Skating drills in ice hockey, running drills in soccer. No head impact activities	Add movement
Non-contact training drills	Progression to more complex training drills, eg passing drills in football and ice hockey. May start progressive resistance training	Exercise, coordination, and cognitive load
Full contact practice	Following medical clearance participate in normal training activities	Restore confidence and assess functional skills by coaching staff
Return to play	Normal game play	

There should be at least 24 hours (or longer) for each stage and if symptoms recur the athlete should rest until they resolve once again and then resume the program at the previous asymptomatic stage. Resistance training should only be added in the later stages.

If the athlete is symptomatic for more than 10 days, then consultation by a medical practitioner who is expert in the management of concussion, is recommended.

Medical clearance should be given before return to play.

Scoring Summary:

Test Domain	Score		
	Date:	Date:	Date:
Number of Symptoms of 22			
Symptom Severity Score of 132			
Orientation of 5			
Immediate Memory of 15			
Concentration of 5			
Delayed Recall of 5			
SAC Total			
BESS (total errors)			
Tandem Gait (seconds)			
Coordination of 1			

Notes:

CONCUSSION INJURY ADVICE

(To be given to the **person monitoring** the concussed athlete)

This patient has received an injury to the head. A careful medical examination has been carried out and no sign of any serious complications has been found. Recovery time is variable across individuals and the patient will need monitoring for a further period by a responsible adult. Your treating physician will provide guidance as to this timeframe.

If you notice any change in behaviour, vomiting, dizziness, worsening headache, double vision or excessive drowsiness, please contact your doctor or the nearest hospital emergency department immediately.

Other important points:

- Rest (physically and mentally), including training or playing sports until symptoms resolve and you are medically cleared
- No alcohol
- No prescription or non-prescription drugs without medical supervision. Specifically:
  - No sleeping tablets
  - Do not use aspirin, anti-inflammatory medication or sedating pain killers
- Do not drive until medically cleared
- Do not train or play sport until medically cleared

Clinic phone number

Patient's name

Date/time of injury

Date/time of medical review

Treatingphysician

Contact details or stamp